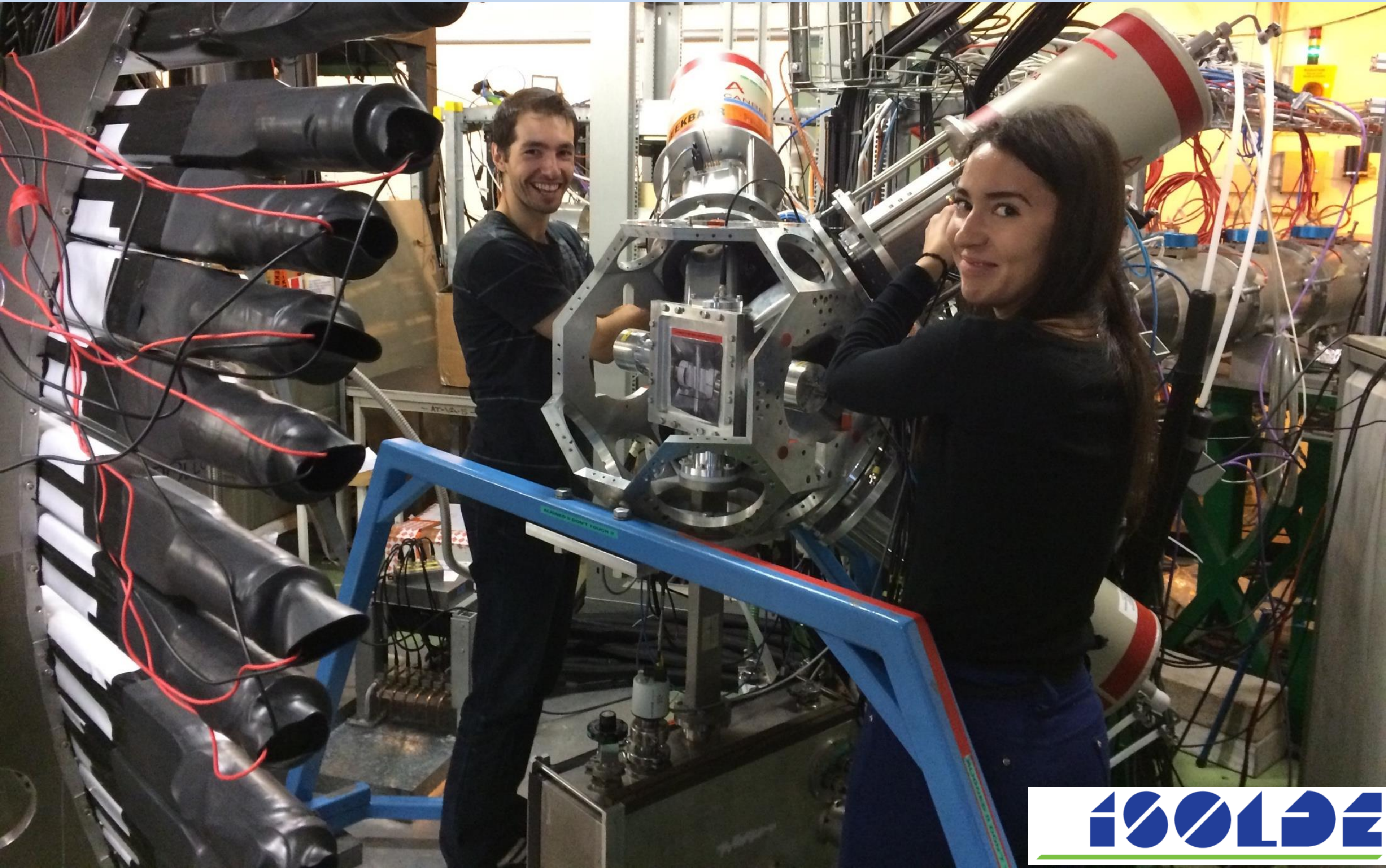
Beta-delayed neutron spectroscopy at the ISOLDE decay station

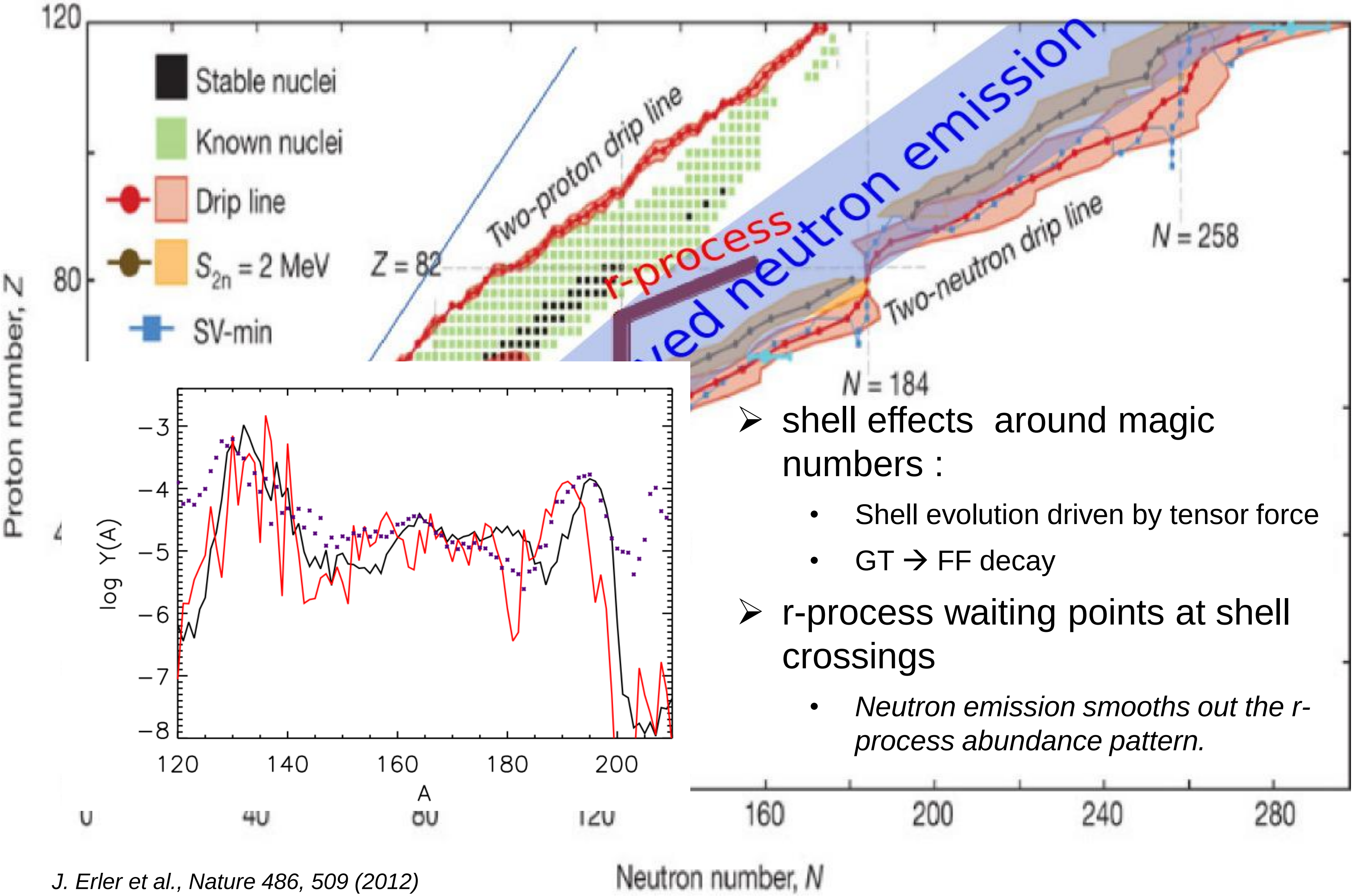
M. Madurga



Outline

- Introduction: beta-delayed neutron emission
- The ISOLDE Decay Station and VANDLE array
- Beta delayed neutron emission of fission fragments
- Beta decay of ^{132}Cd @ IDS (preliminary!)

Beta-decay properties near major shell gaps for neutron rich nuclei



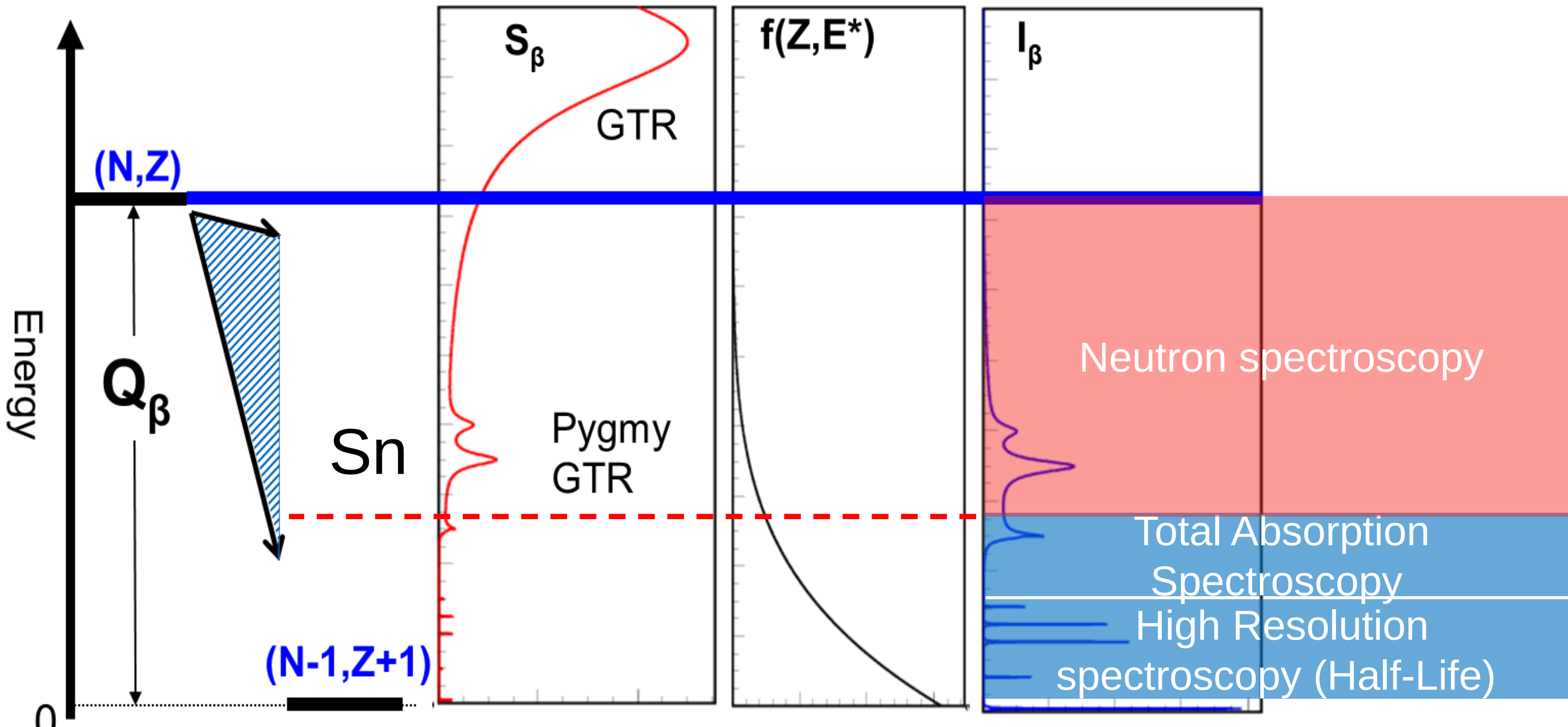
- shell effects around magic numbers :
  - Shell evolution driven by tensor force
  - GT → FF decay
- r-process waiting points at shell crossings
  - *Neutron emission smooths out the r-process abundance pattern.*

J. Erler et al., Nature 486, 509 (2012)

Beta decay of neutron rich nuclei: Comprehensive measurements

$$\frac{1}{T_{1/2}} = \sum_{E_i \geq 0}^{E_i \leq Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i)$$

$$S_\beta(E_i) = \langle \psi_f | \hat{O}_\beta | \psi_{mother} \rangle$$



A multipurpose Decay spectroscopy setup for ISOLDE

The **I**SOLDE **D**ecay **S**tation (**IDS**) project aimed to provide:

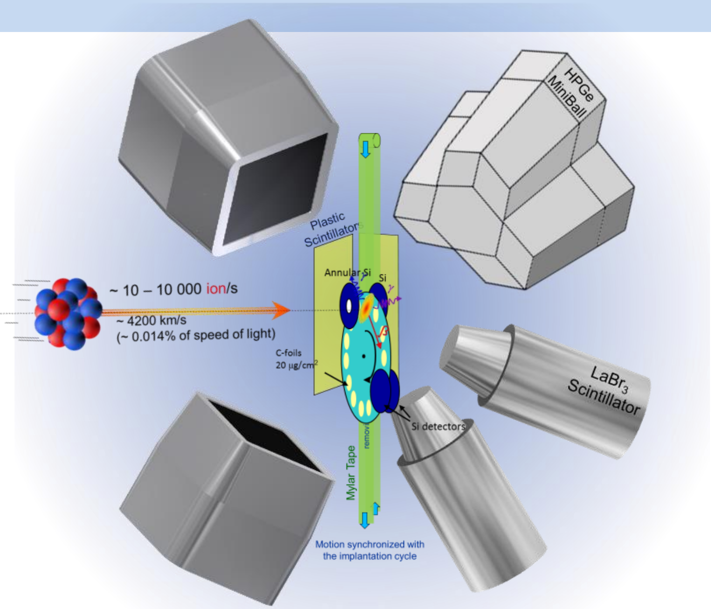
- **Permanent** Setup for decay studies using the RIB from ISOLDE
- **Flexible** (for several decay types or studies)

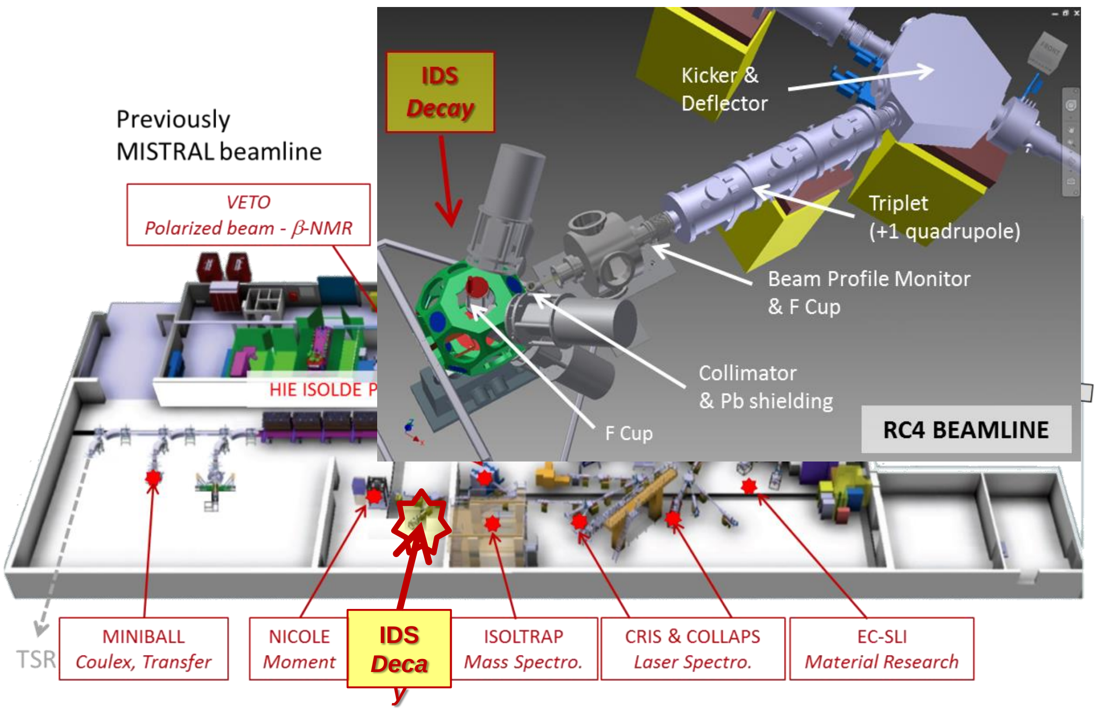
Basic approach:

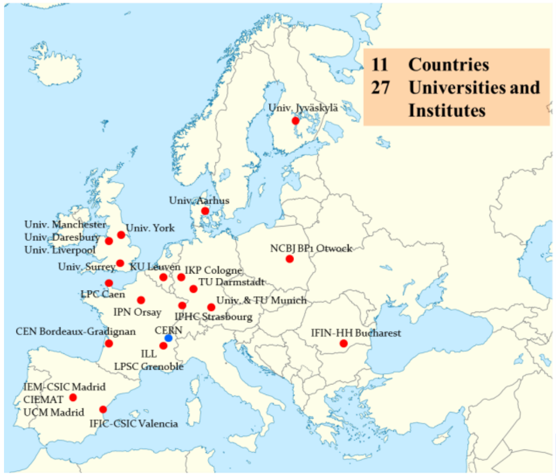
High Pure Ge-detector (4 clovers and up to 3 MiniBall detectors)

+ Ancillary detectors ($LaBr_3$, plastic scintillator, silicon, neutron detectors, …)

+ Tape station/Windmill implantation chamber





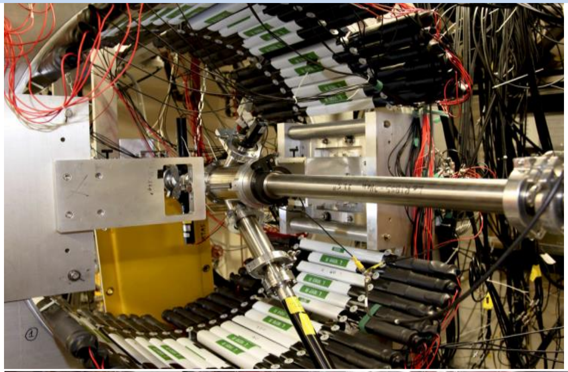


Belgium (KU Leuven - IKS)
Denmark (Univ. of Aarhu)
Finland (Univ. of Jyväskylä)
France (CEN Bordeaux-Gradignan; IPHC Strasbourg; LPC Caen; LPSC Grenoble; IPN Orsay; Univ. Paris Sud; ILL)
Germany (IKP - TU Darmstadt; IKP- Univ. zu Köln; Univ. zu München; TU München)
Poland (NCBJ BP1 Otwock)
Romania (IFIN-HH Bucharest)
Spain (CIEMAT Madrid; IEM-CSIC Madrid; IFIC-CSIC Valencia; UCM Madrid)
Sweden (Univ. of Lund)
Switzerland (CERN - ISOLDE)
UK (STFC Daresbury Lab.; Univ. of Liverpool; Univ. of Manchester; Univ. of Surrey; Univ. of York)

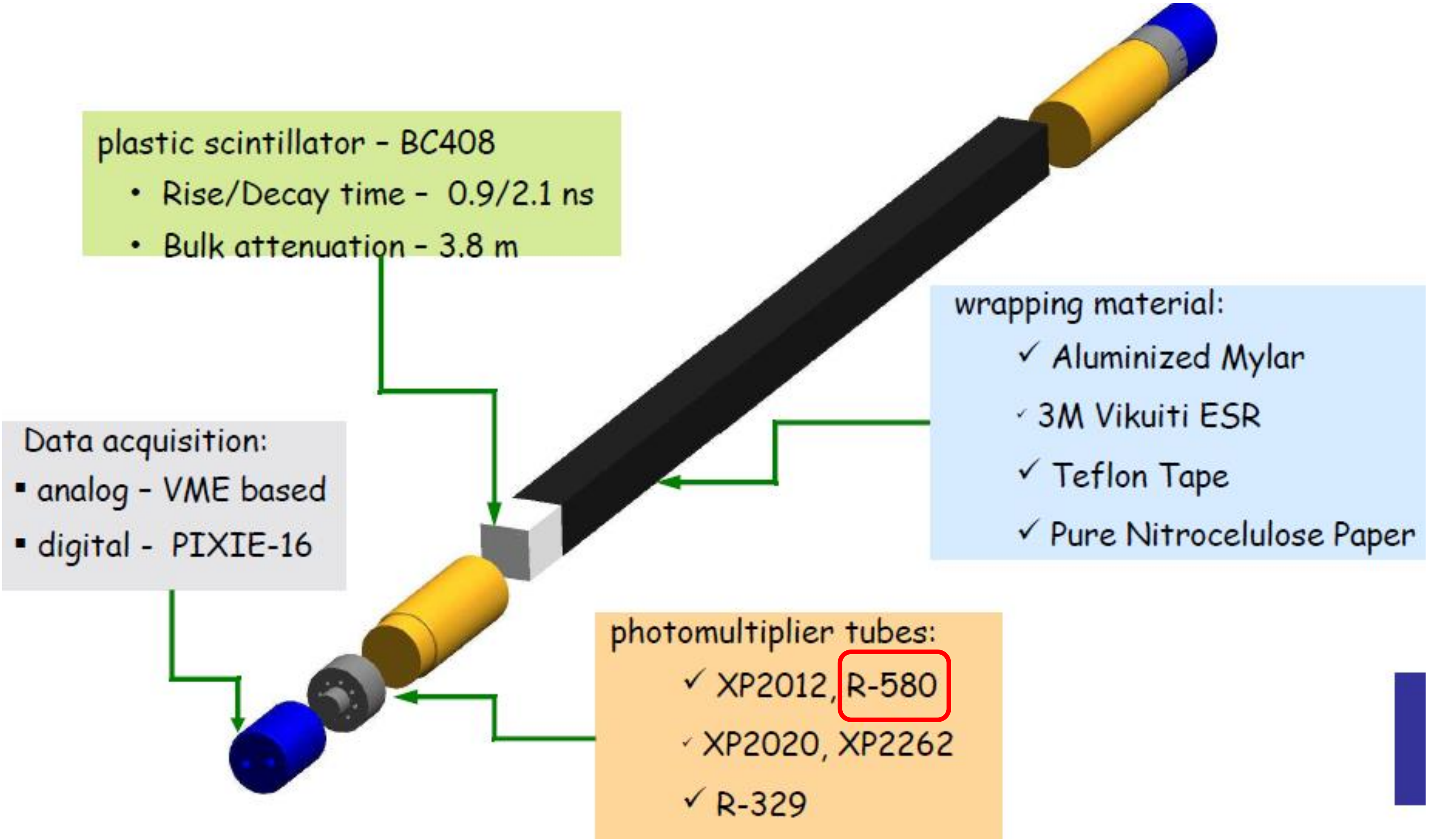
PHASE 1 focused on β-decay studies

The Versatile Array of Neutron Detectors at Low Energy

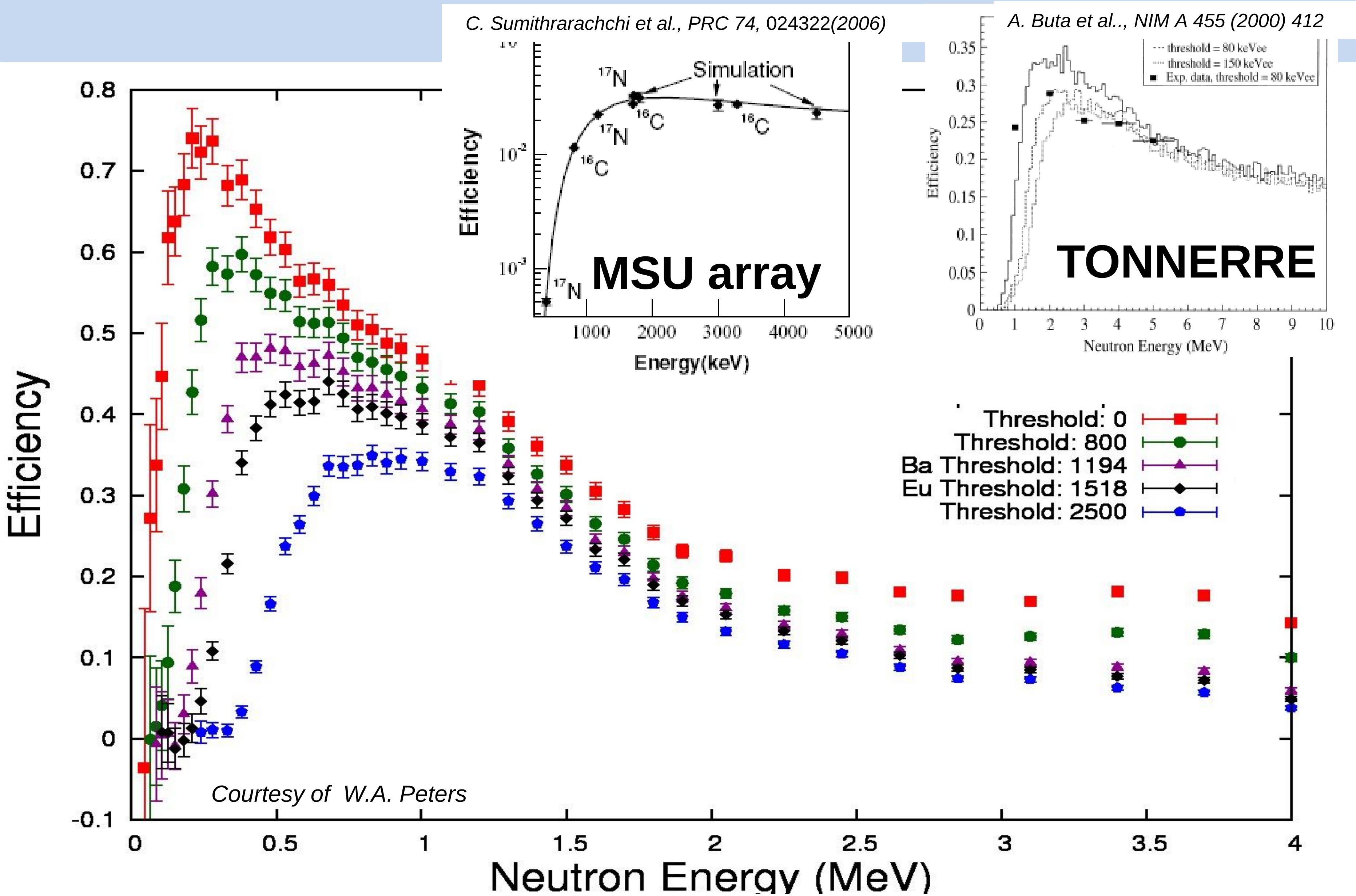
- A highly modular array of plastic scintillators for neutron Time-of-Flight measurement
- Scientific goals: β-delayed neutrons and reaction studies.
- Bar Sizes:
  - Small : 3x3x60 cm3
  - Medium : 3x6x120 cm3
  - Large : 5x5x200 cm3
- Neutron Energies Covered:
  - Small/Med. : 0.1 - 6 MeV
  - Large : 1 - 20 MeV



Detector components



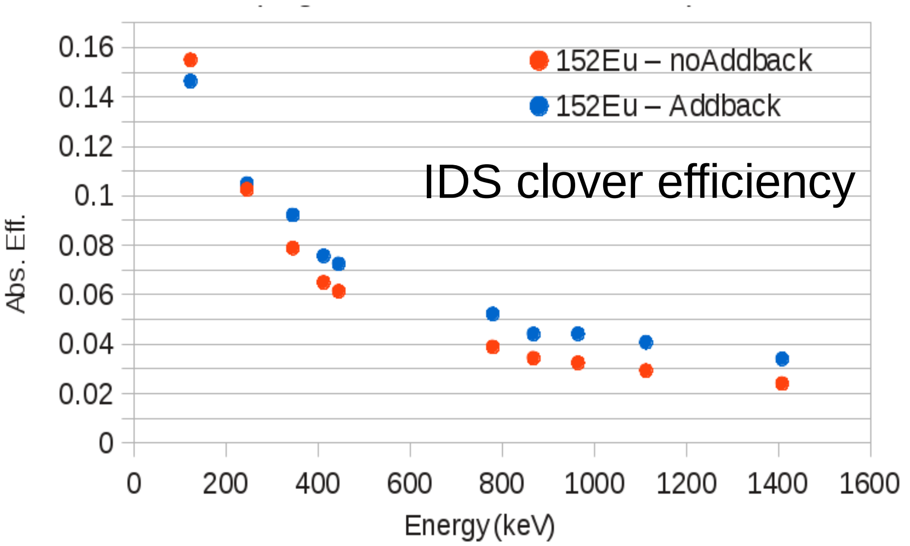
Highly improved low energy neutron efficiency

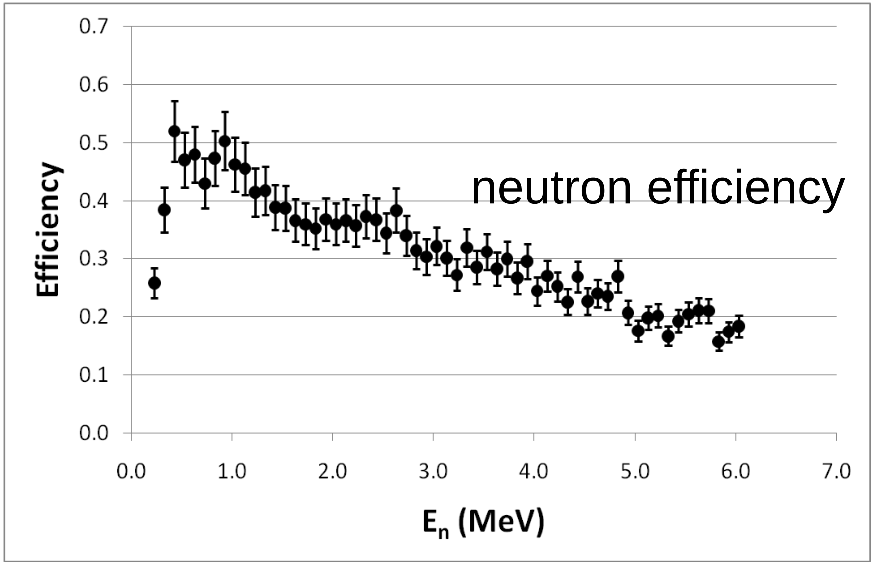


Neutron spectroscopy @ IDS

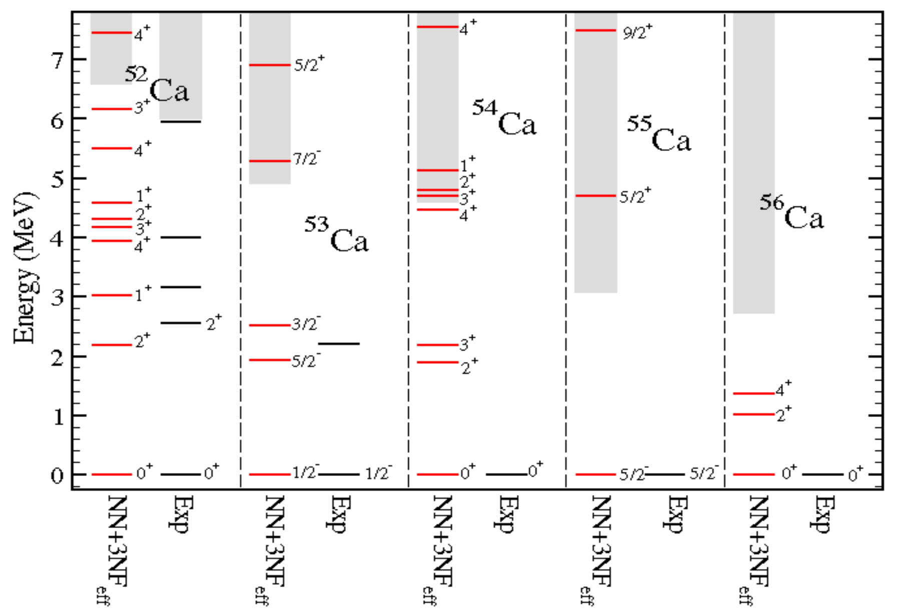
- 4 clovers, 4% efficient @ 1MeV
- 26 x 120 cm VANDLE bars
  - •45% efficiency/bar @ 1MeV
  - •Ω = 14.9% of 4π
  - •90% β-trigger efficiency
  - •<u>6% total efficiency @ 1MeV</u>

  (possible efficiency increase to 9% in 2016)



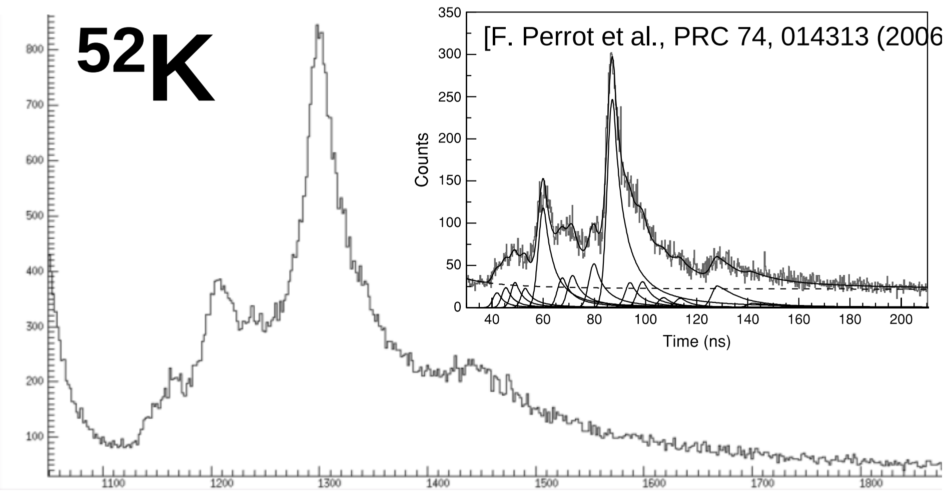


IS599: Study of neutron-rich 51-53Ca isotopes via beta-decay

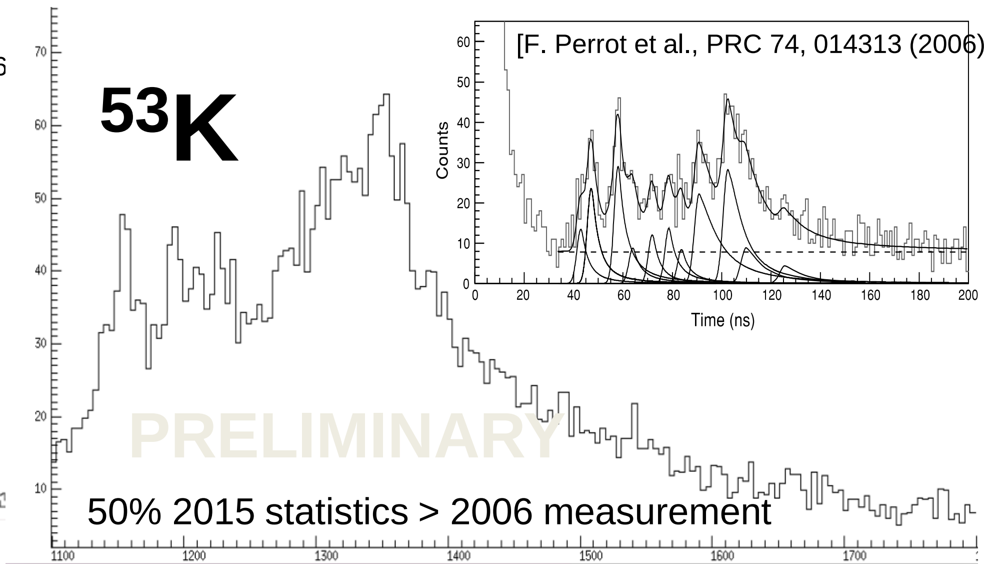


- Potassium isotopes @ IDS:
  - Search for single particle states in odd Ca isotopes
  - Greatly improved statistics

More details in talk by A. Gottardo



Time (ns *4 + 1000)



Time (ns *4 + 1000)

Beta delayed neutron emission from fission fragments ~40 y history

Delayed neutron spectroscopy field extremely active after development of ^{3}He ion chambers (PRL,PLB, etc…)

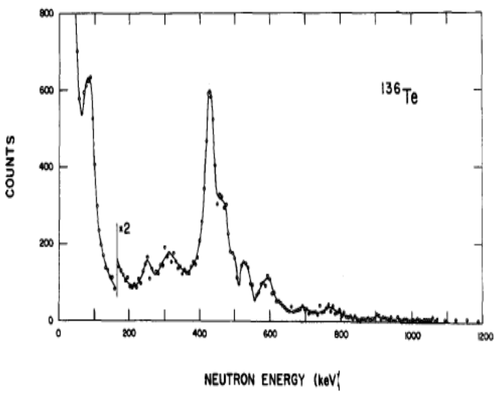
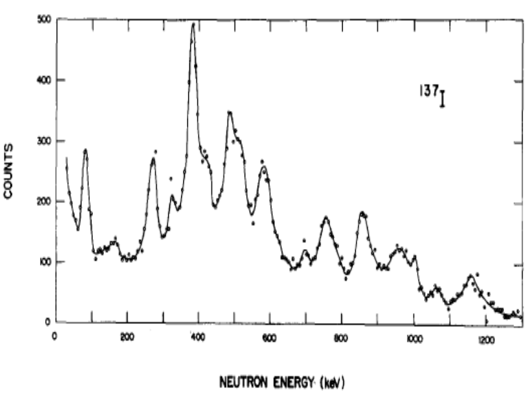
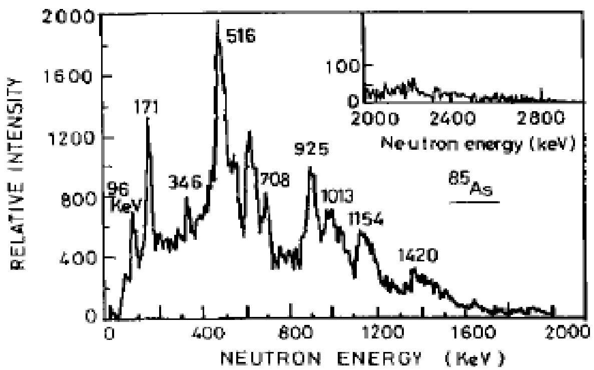
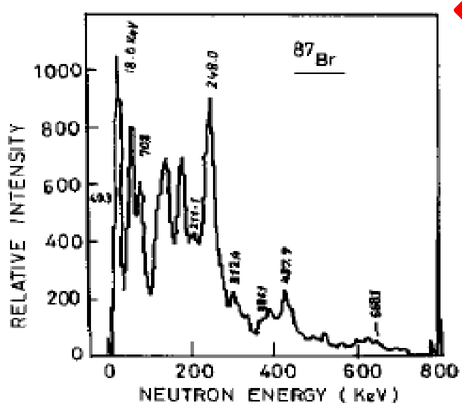


Fig. 9. The pulse height spectrum of delayed neutrons from the precursor ^{136}Te.



G. Rudstam et al. (Studsvik)





K.L. Kratz et al. (Mainz,ISOLDE)

1.E.4 Nuclear Physics A305 (1978) 15–28; © North-Holland Publishing Co., Amsterdam

THE ESSENTIAL DECAY OF PANDEMONIUM: β-DELAYED NEUTRONS

J. C. HARDY †, B. JONSON †† and P. G. HANSEN †††
CERN, Geneva, Switzerland

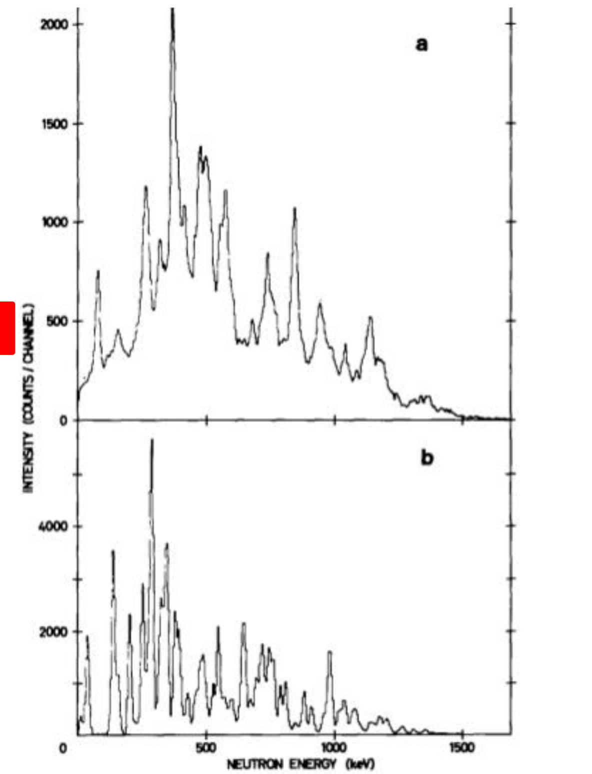
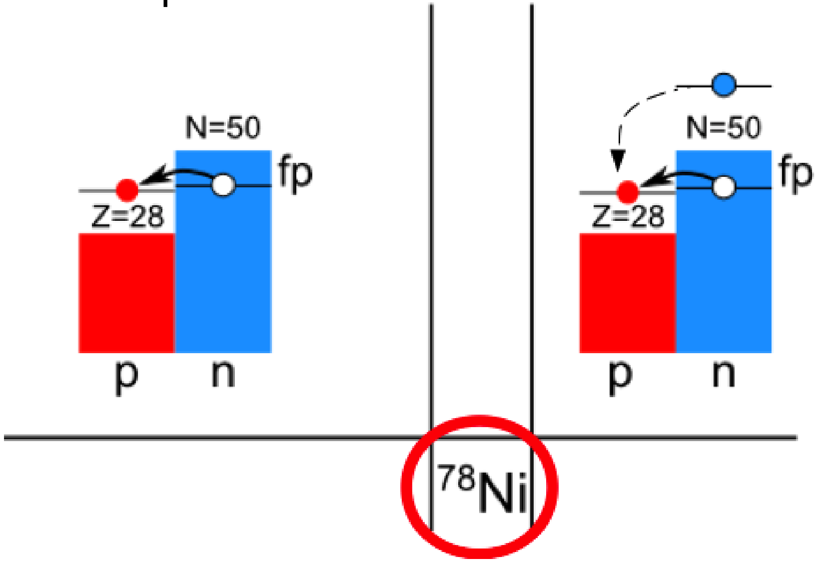
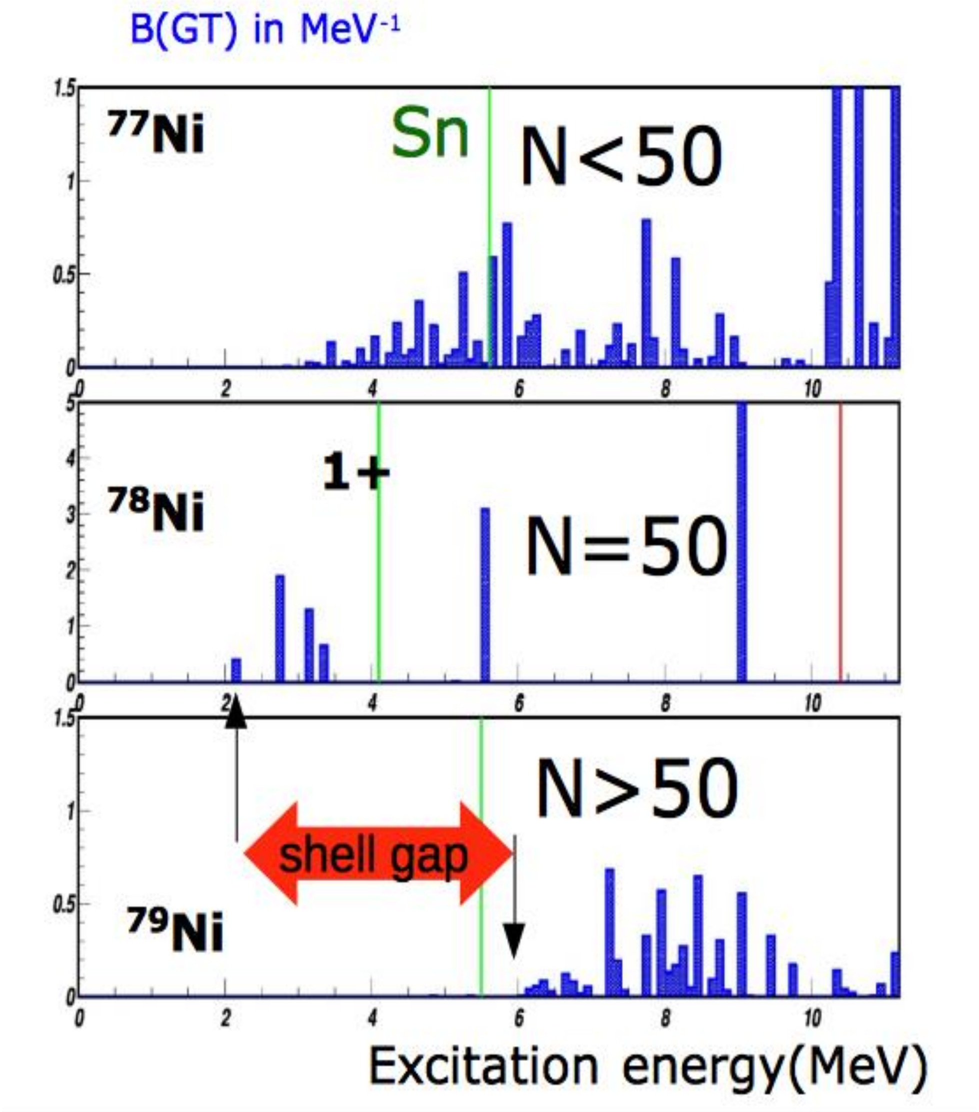


Fig. 3. Comparison between (a) experiment [3]) and (b) pandemonium simulation for the delayed neutron spectrum from the decay of ^{137}I.

Effects of the shell gap on the decay of isotopes with beyond a major shell gap

- Gamow-Teller operator can only connect spin orbit partners
- For N>50 competing decay types
  - Valence neutron decay is of forbidden type
  - GT decay of core neutrons is orders of magnitude stronger but suppressed by Fermi phase space



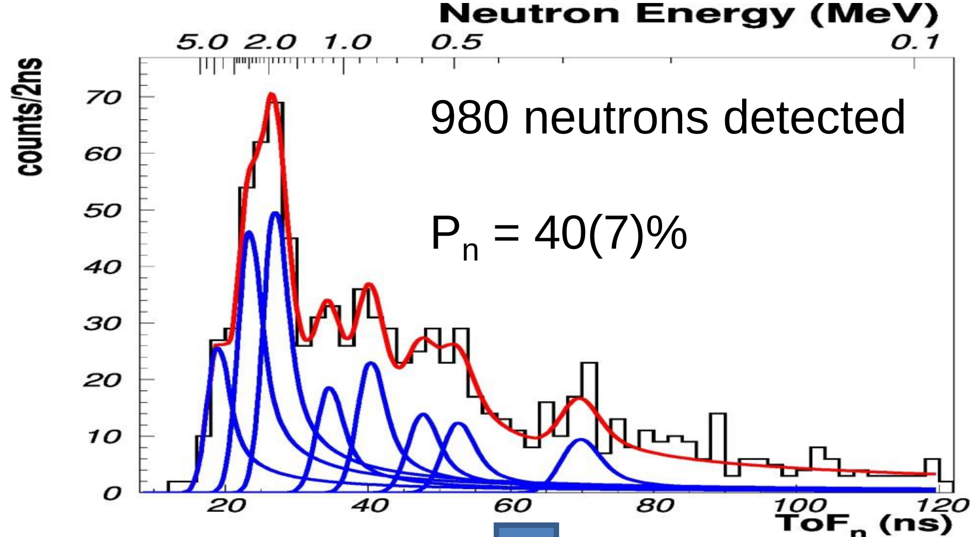


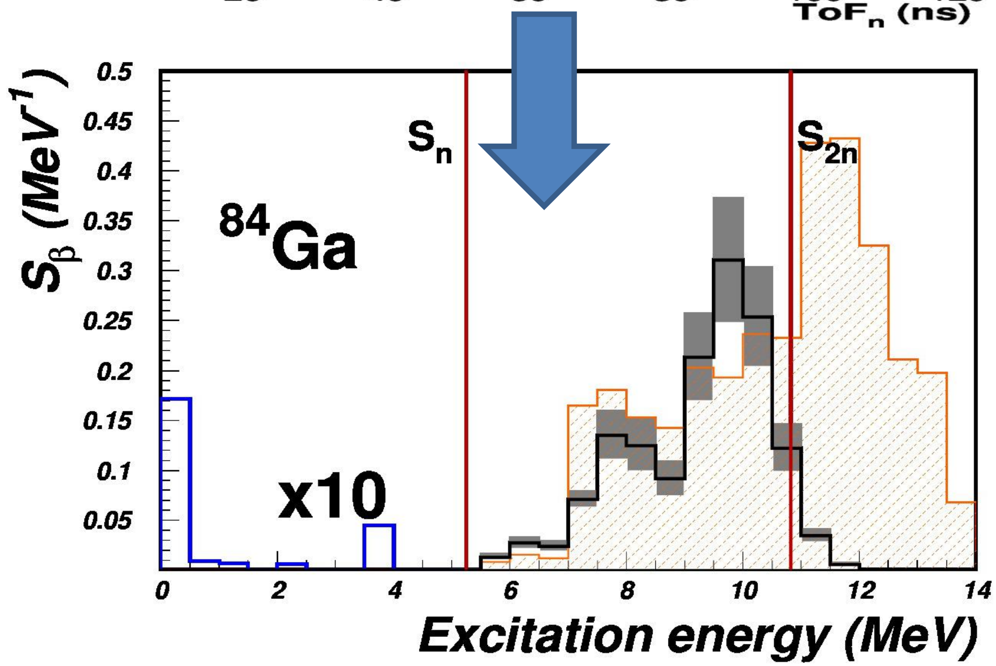
^{84}Ga @ ORNL

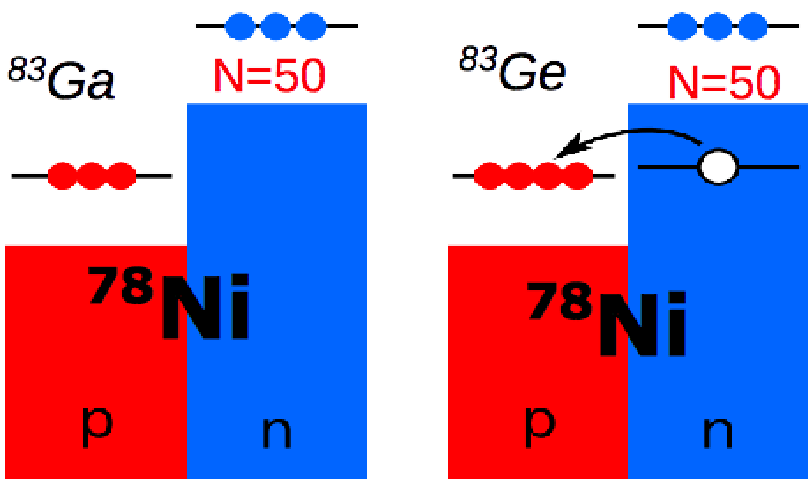
- Neutron branching ratio **<u>different</u>** from literature 70(13)% and 74(14)%

[K.-L. Kratz et al., Z. Phys. A ***340****, 419 (1991)]*
[J.A. Winger et al. PRC 81, 044303(2010)]

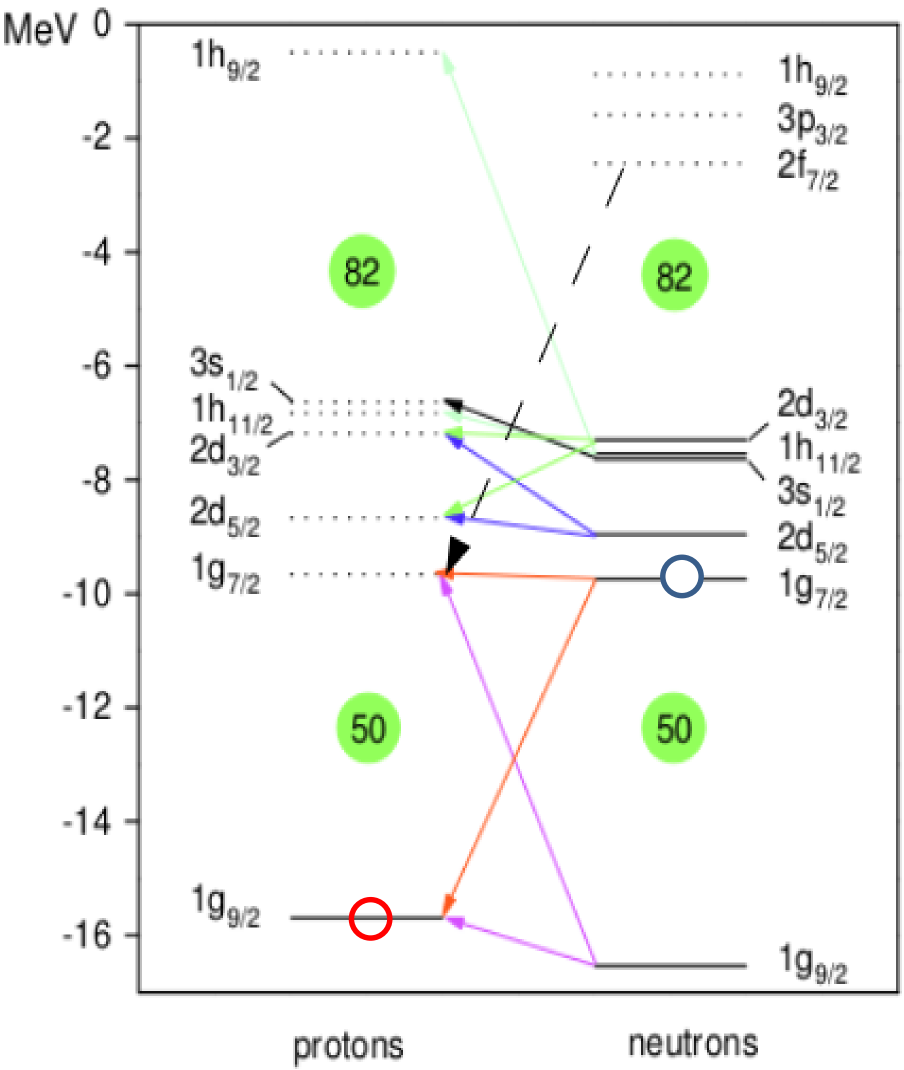
- Nushellx calculation with hybrid interactions in good accordance with data:
  - *jj44bpn* for fpg (^{56}Ni core, B.A. Brown),
  - Added matrix elements for neutrons in $d_{5/2}$ x protons and neutrons in fpg





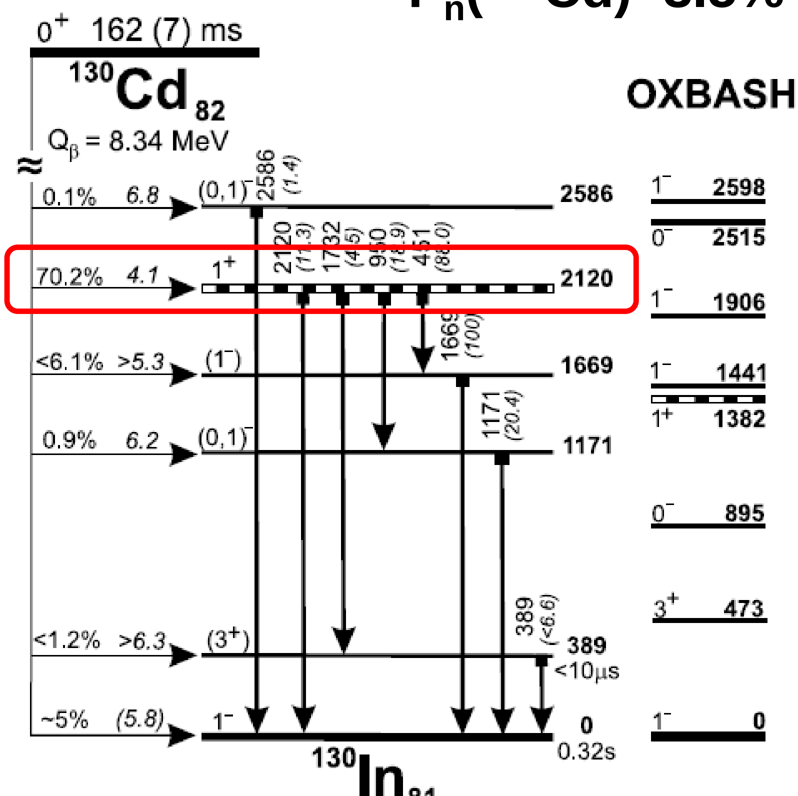


Beta-decay of Cd isotopes around N=82
^{130}Cd



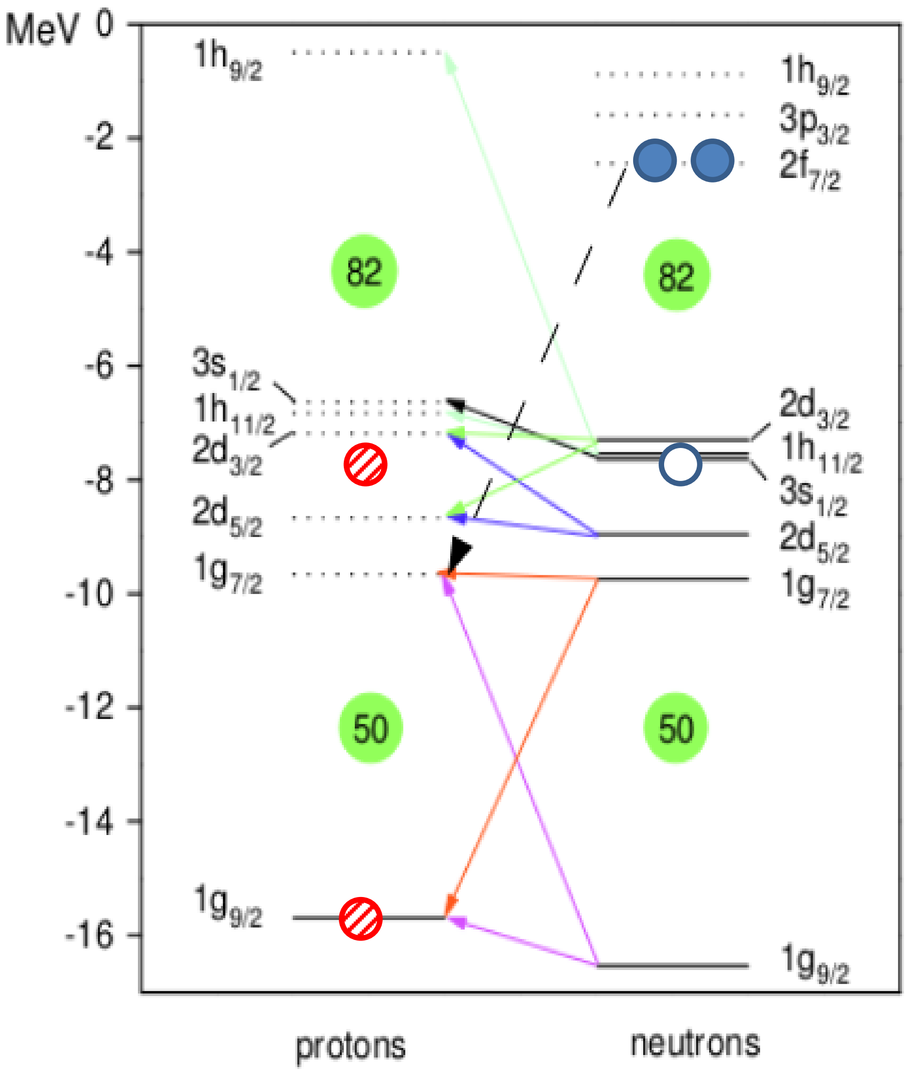
- Low energy states in In driven by SPEs

$P_n(^{131}Cd)=3.5\%$



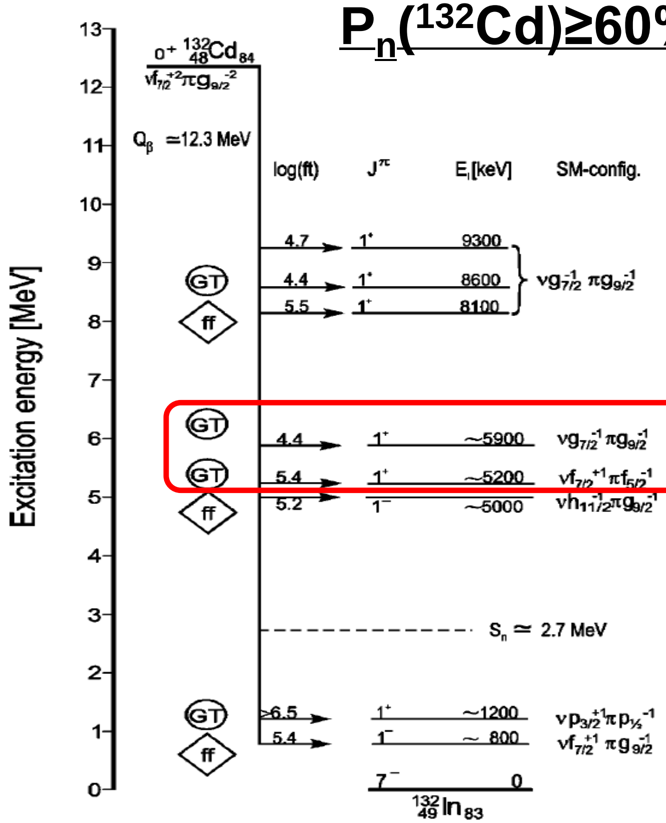
I. Dillmann et al., PRL. 91, 162503 (2003).

Beta-decay of Cd isotopes around N=82
^{132}Cd



- **FF and GT strength separated by N=82 shell gap**
- **Neutron distribution → *v-gdh* single particle states**

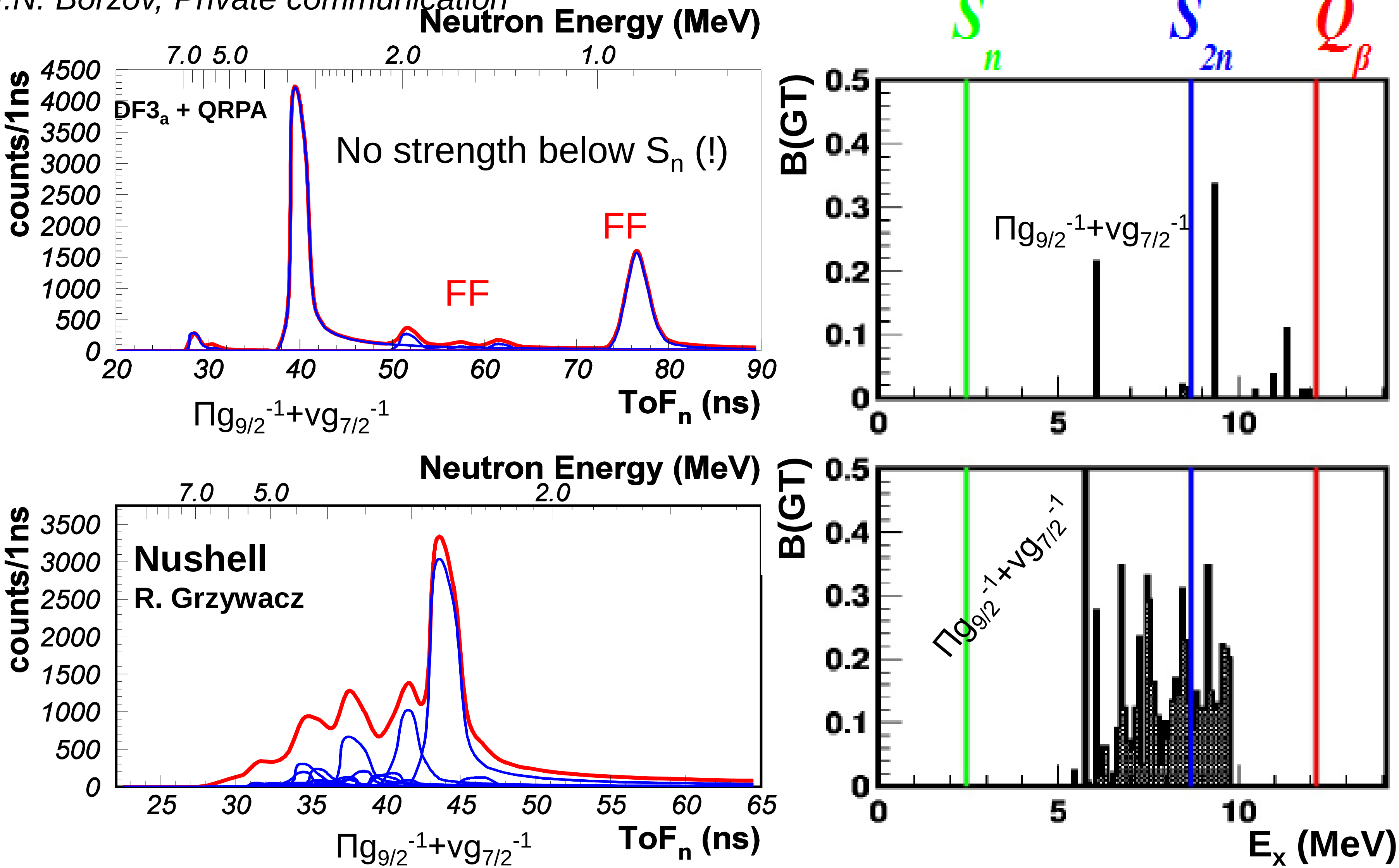
$P_n(^{132}Cd) \geq 60\%$



M. Hannawald et al., PRC 62, 054301 (2000)

^{132}Cd β-decay strength calculations

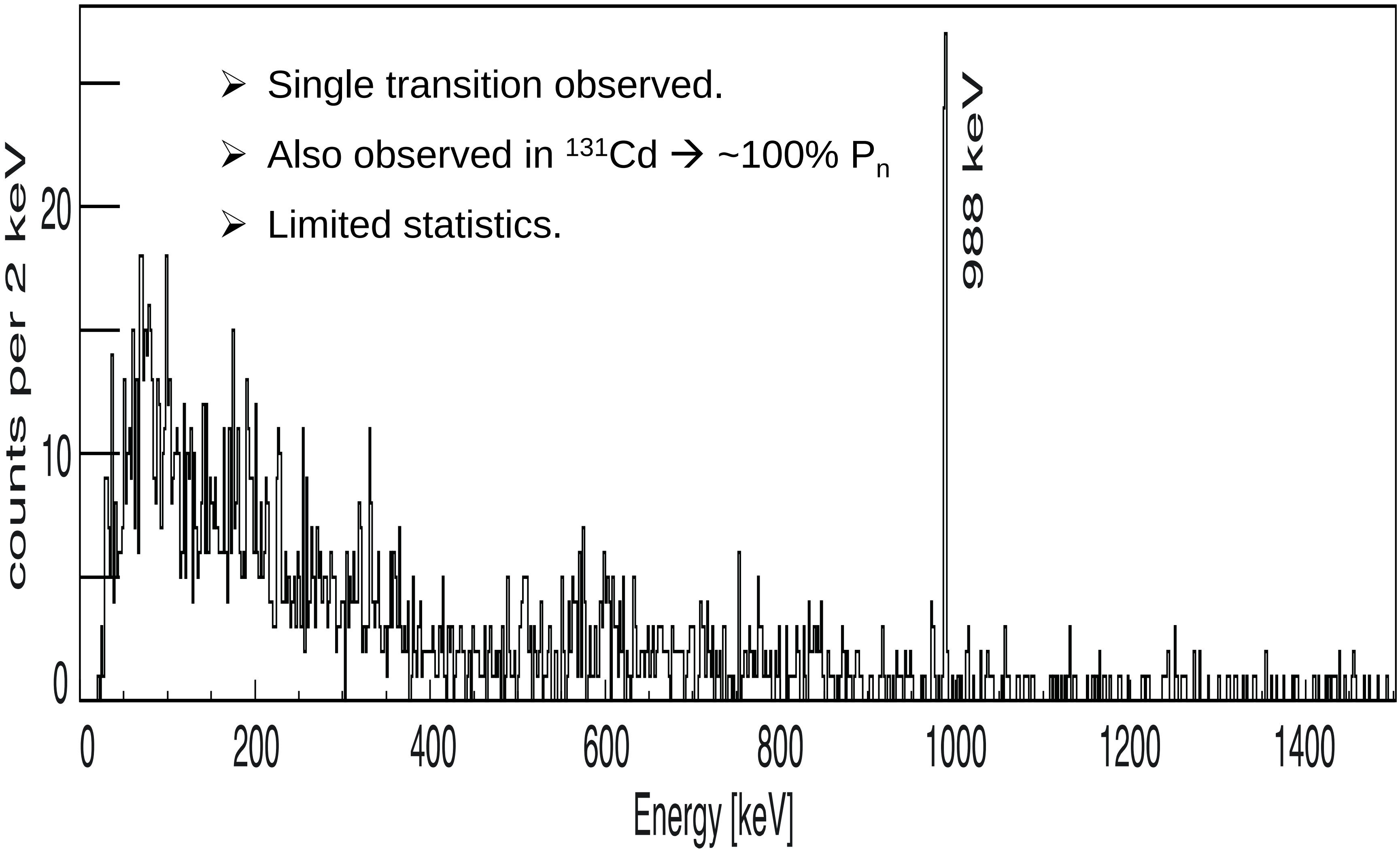
I.N. Borzov, Private communication



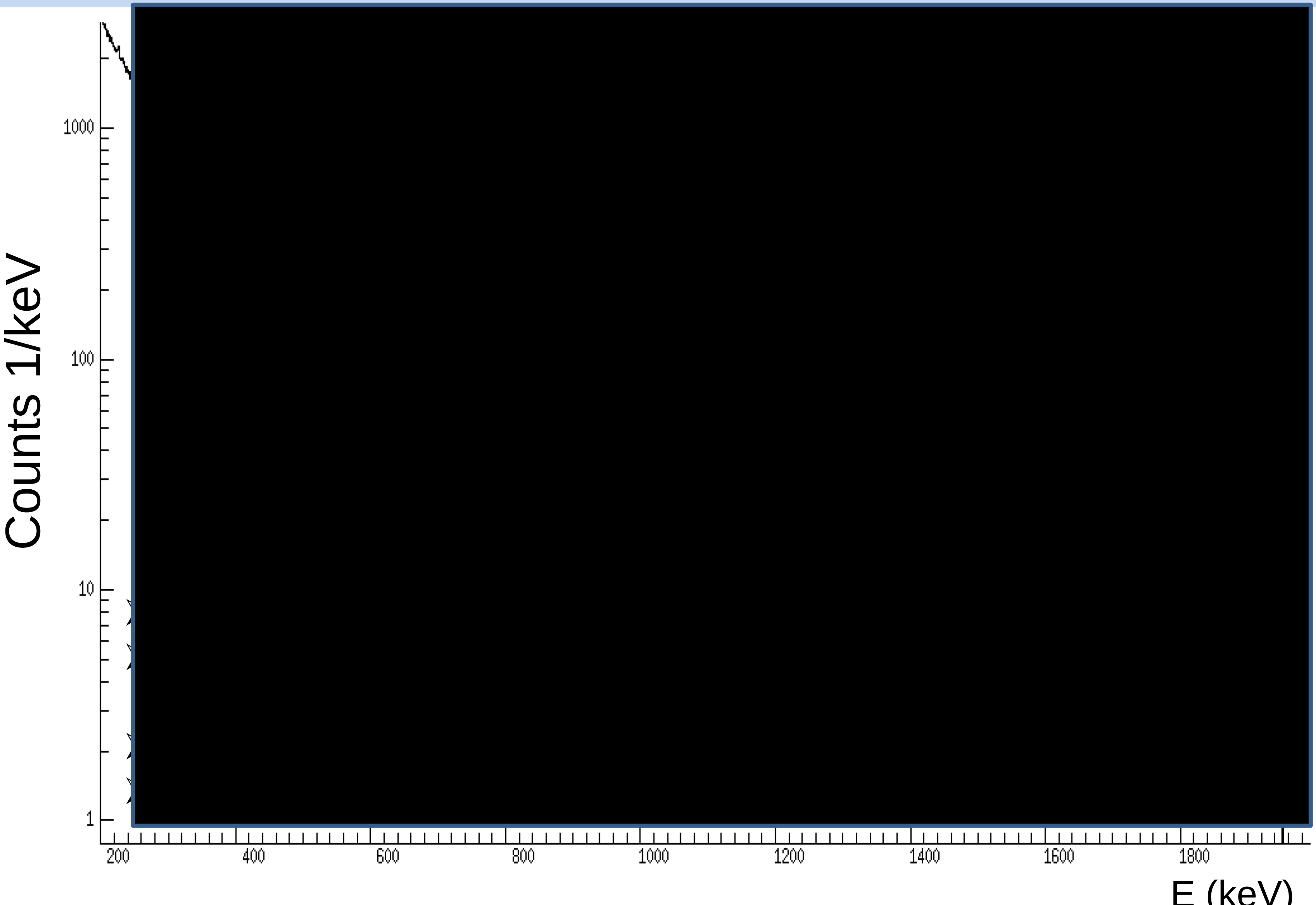
^{132}Cd β-decay @ RIKEN

J.A. Taprogge, thesis dissertation, Universidad Autonoma de Madrid (2015)

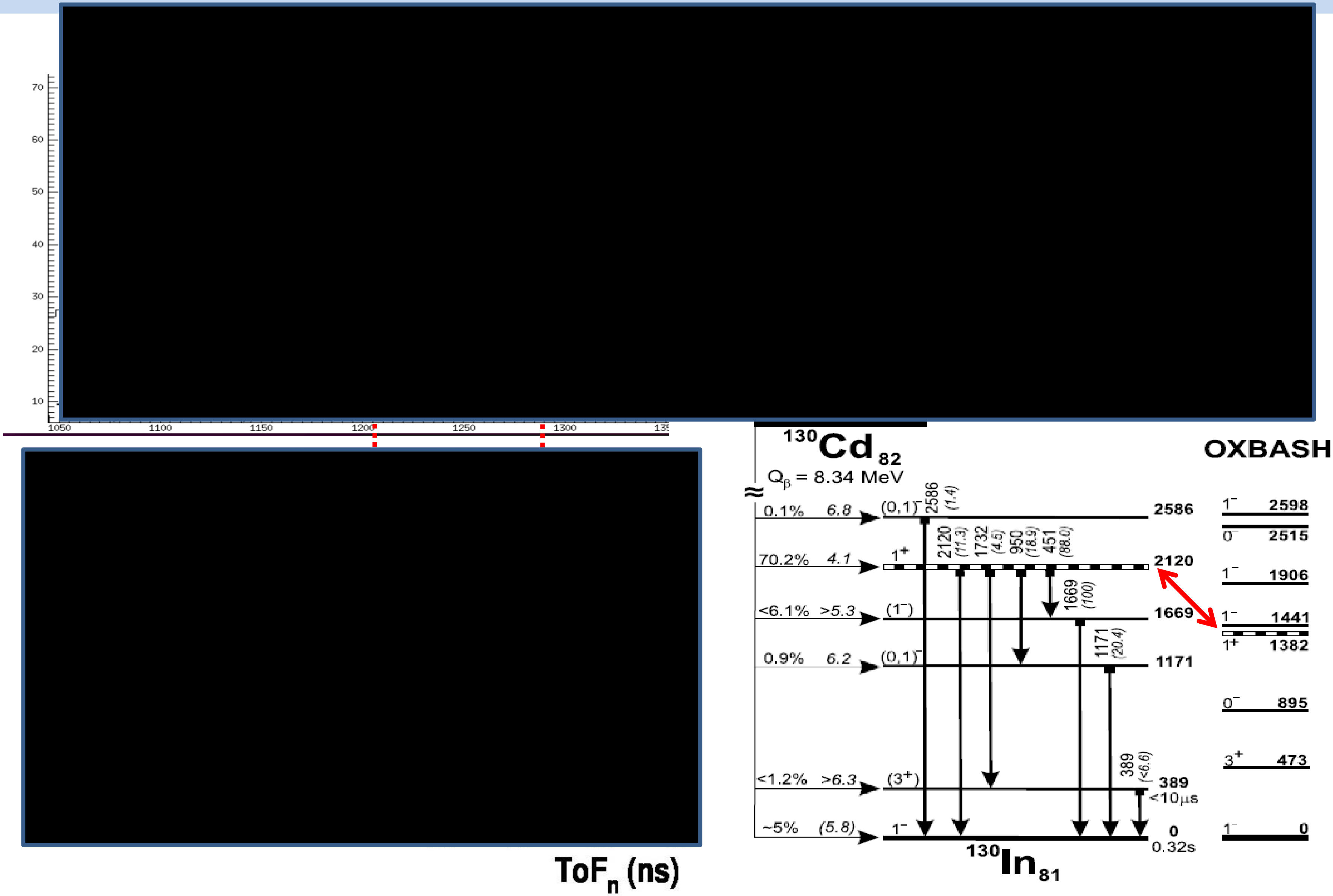
- Single transition observed.
- Also observed in ^{131}Cd → ~100% P_n
- Limited statistics.



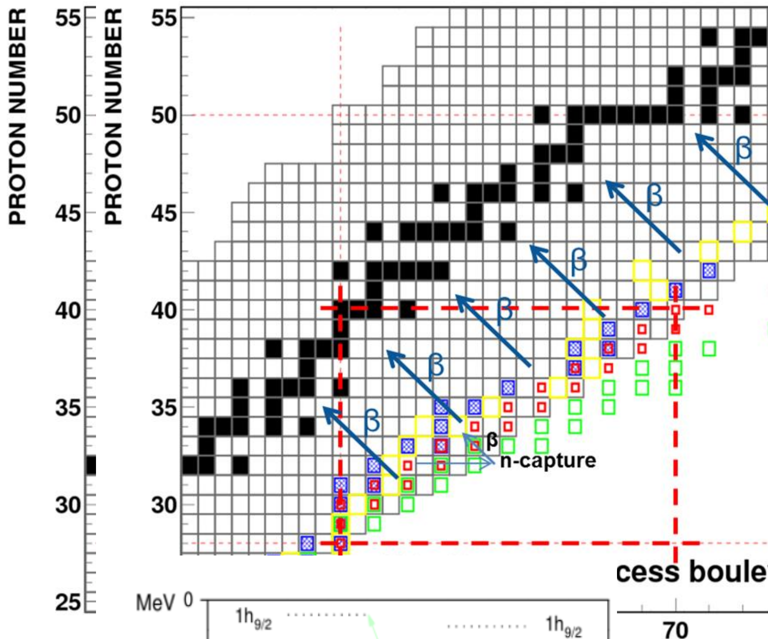
^{132}Cd β-delayed γ-spectrum @ IDS

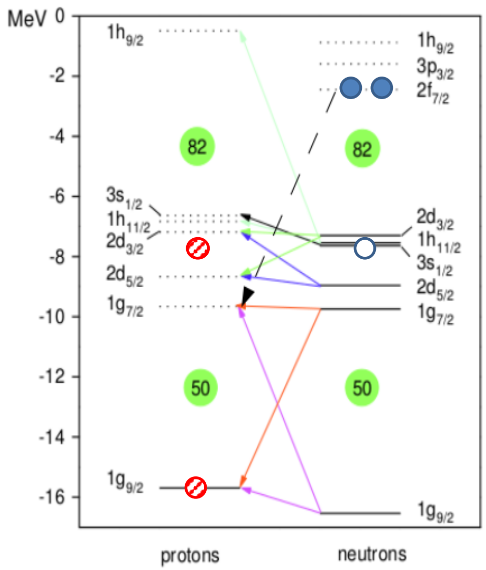


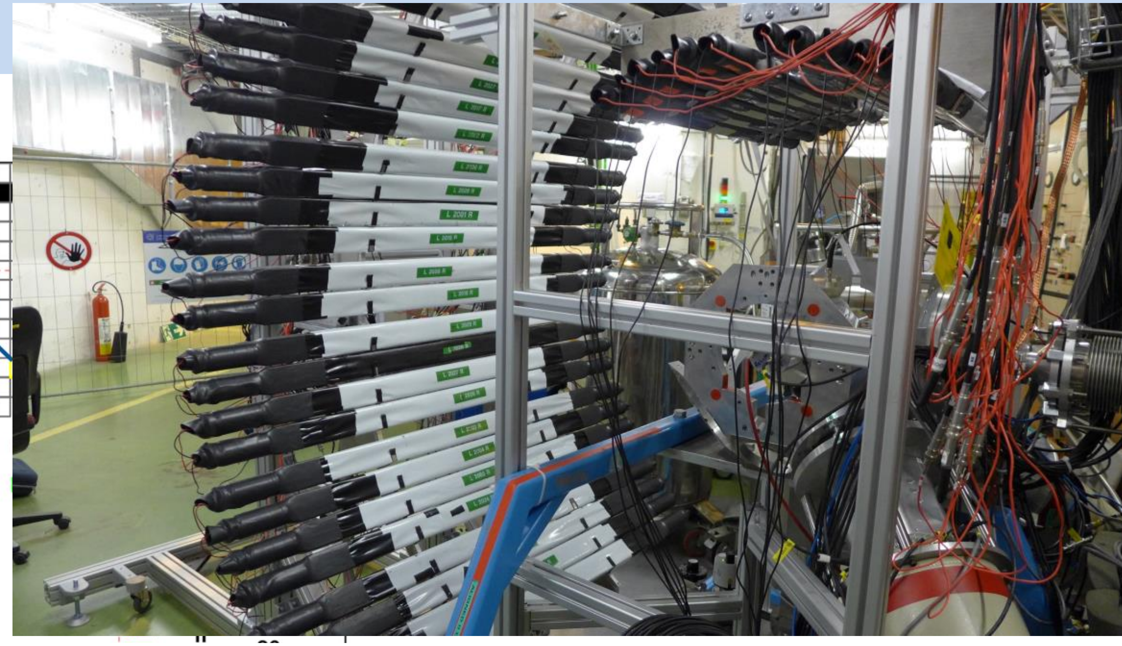
Neutron energy spectrum



Summary







- Beta-delayed neutron emission becoming more a more important as we produce ever more exotic neutron rich species.
- Shell effects enhance neutron emission across major shell gaps
- ^{130}In-^{132}In 1+ states offers a perfect natural experiment for isotopic evolution across N=82 shell gap

IDS + VANDLE Collaborations

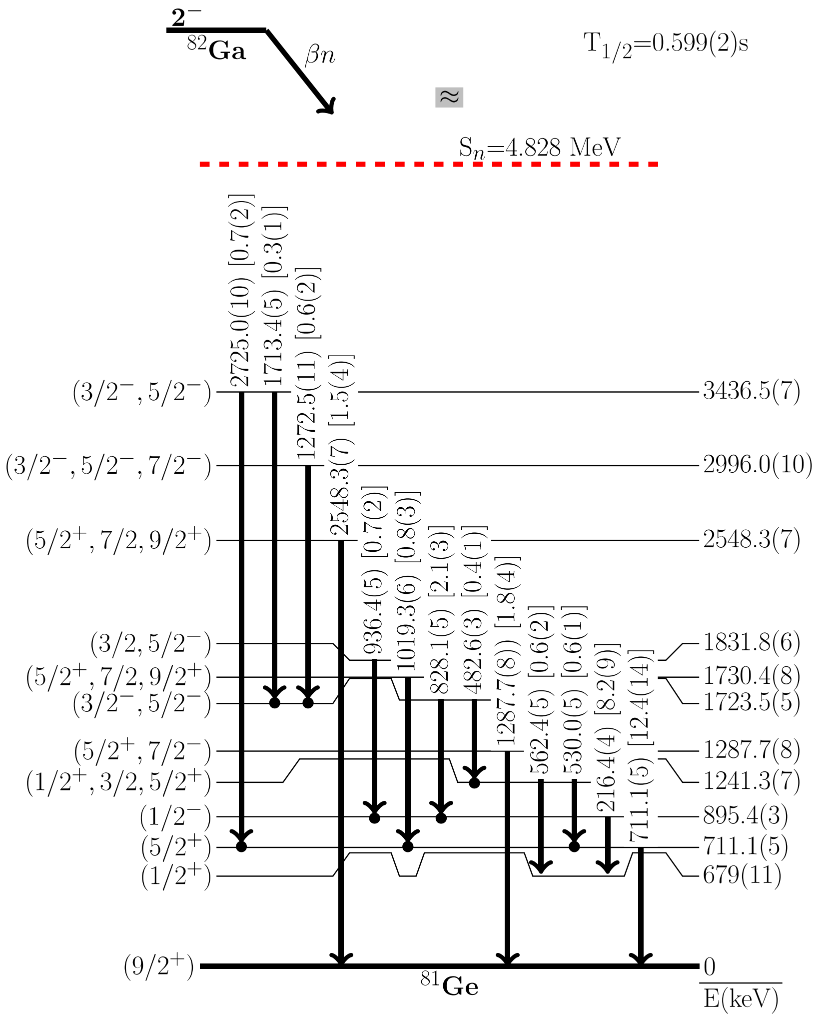
R. Grzywacz[1,3], K. Kolos[1], D. Bardayan[4], M.J.G. Borge[2], N.T. Brewer[3], J.A. Cizewski[5], T. E. Cocolios[6], I. Dillman[7], A. Fijalkowska[8], L.M. Fraile[9], C.J. Gross[3], S.V. Ilyushkin[10], C. Mazzocchi[8], B. Manning[5], K. Miernik[8], D. Miller[7], S.V. Paulauskas[11], W.A. Peters[12], S. Taylor[1],O. Tengblad[13],C. Sotty[14], E. Rapisarda[1], K. P. Rykaczewski[3],V. Vedia[9], N. Warr[15], H. De Witte[14], Y. Xiao[1]

[1]Univesity of Tennessee
[2]CERN.
[3]Oak Ridge National Laboratory
[4]University of Notre Dame, Notre Dame, Indiana 46556, USA.
[5]Rutgers University
[6]The University of Manchester,
[7]TRIUMF
[8]University of Warsaw,
[9]Universidad Complutense de Madrid
[10]Colorado School of Mines
[11]National Superconducting Cyclotron Laboratory
[12]Joint Institute for Heavy-Ion Research
[13]Instituto de Estructura de la Materia, CSIC.
[14]KU Leuven, University of Leuven.
[15] TU. Köln

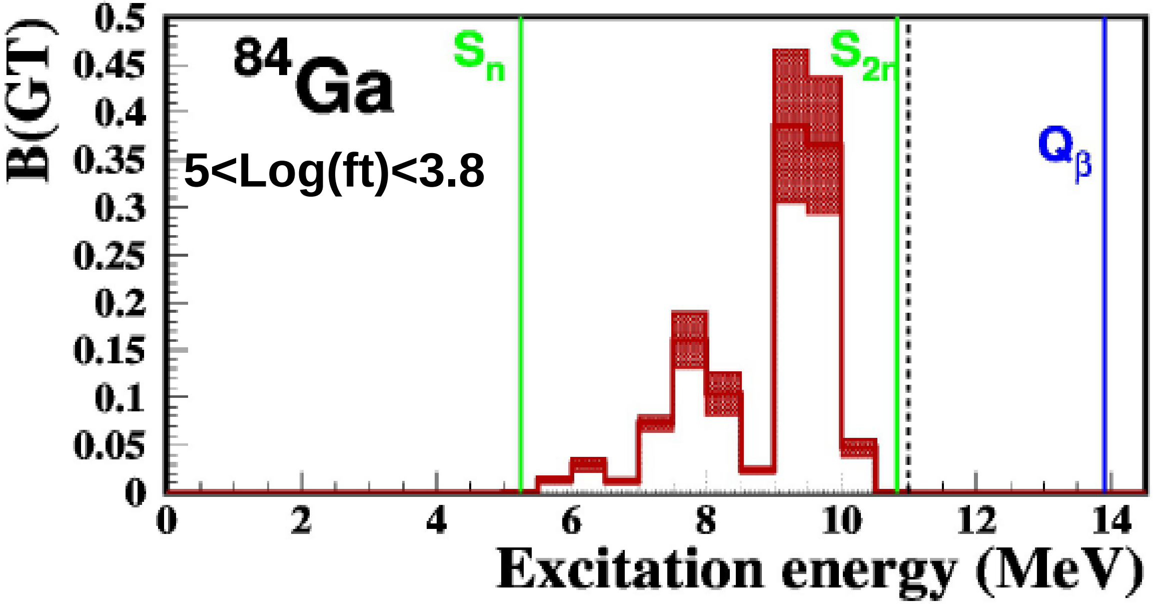
BACK UP SLIDES

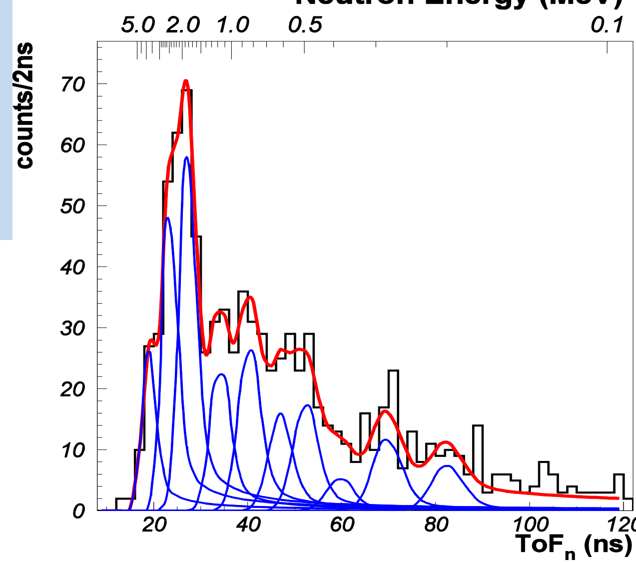
Beta decay of 82Ga

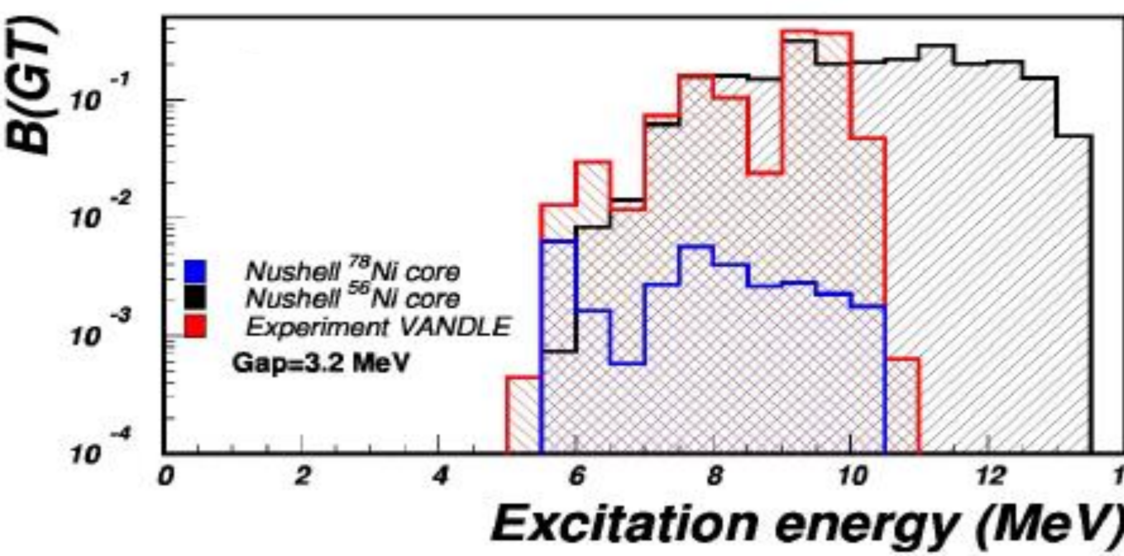
M. Al-shudifat et al., submitted to PRC

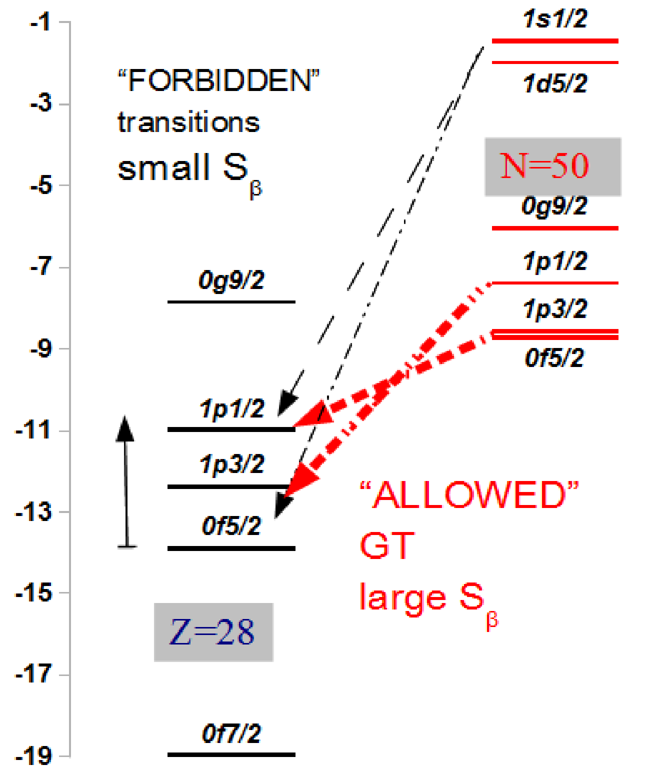


Core breaking states in ^{84}Ga

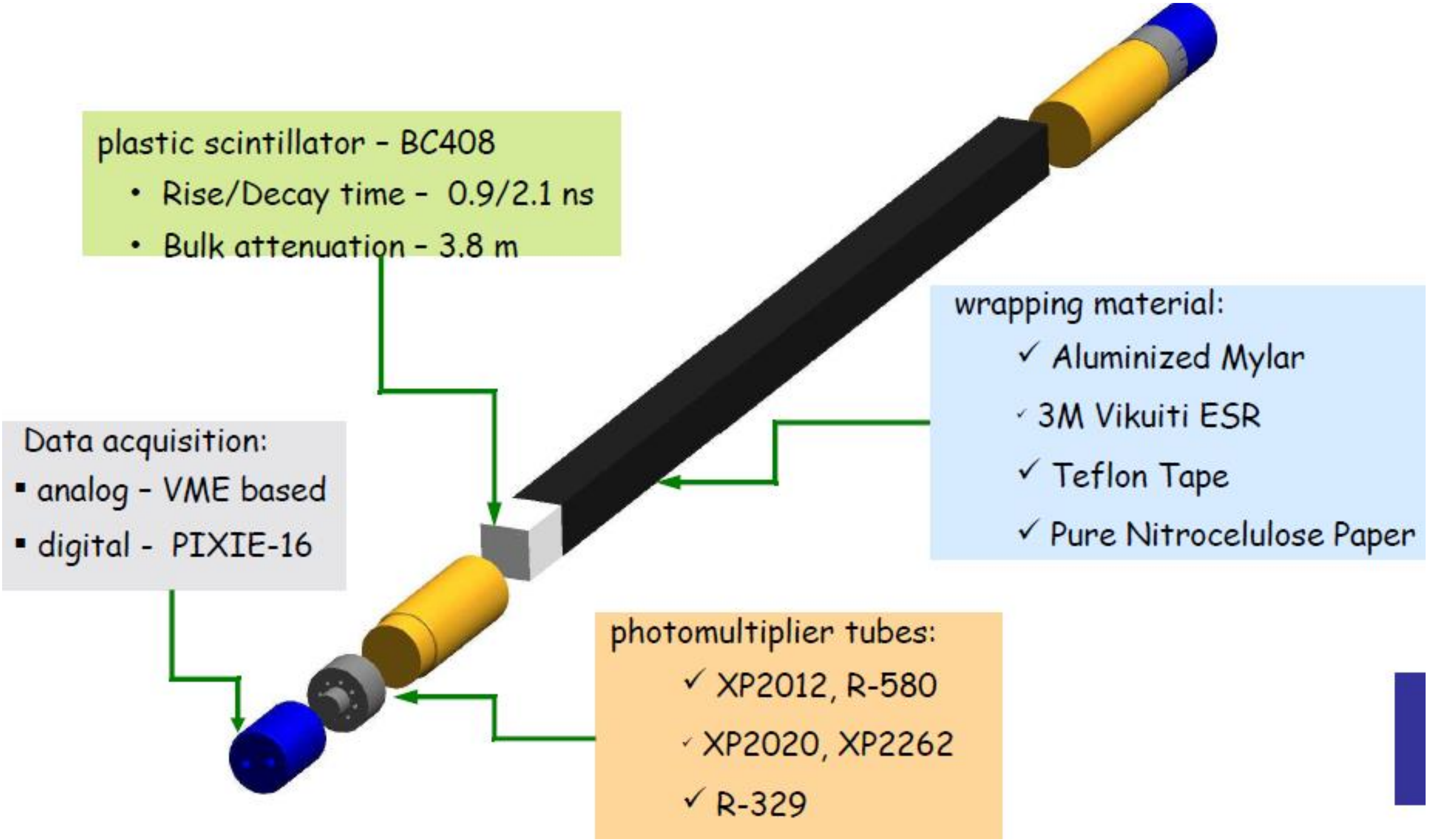






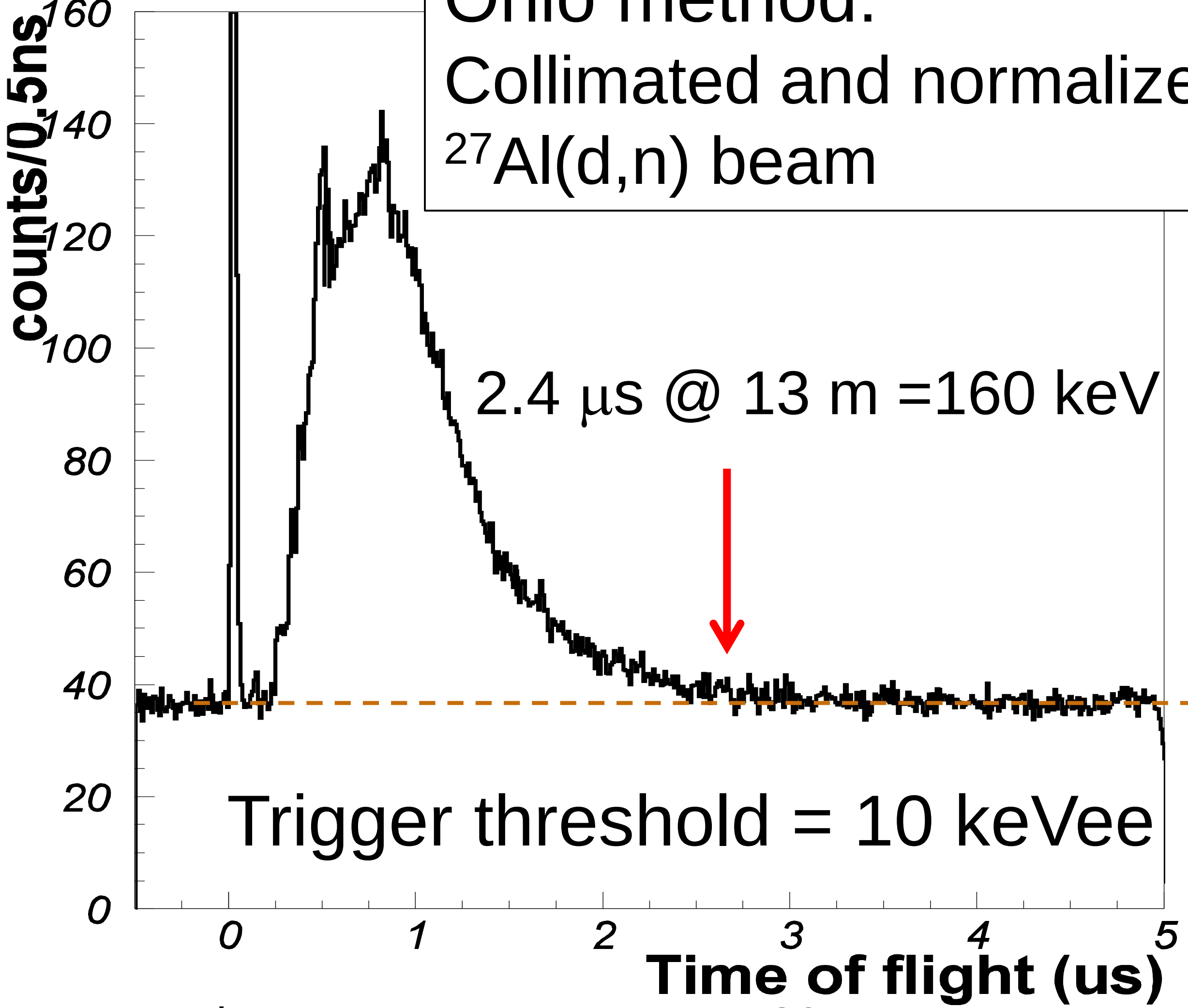


Detector components

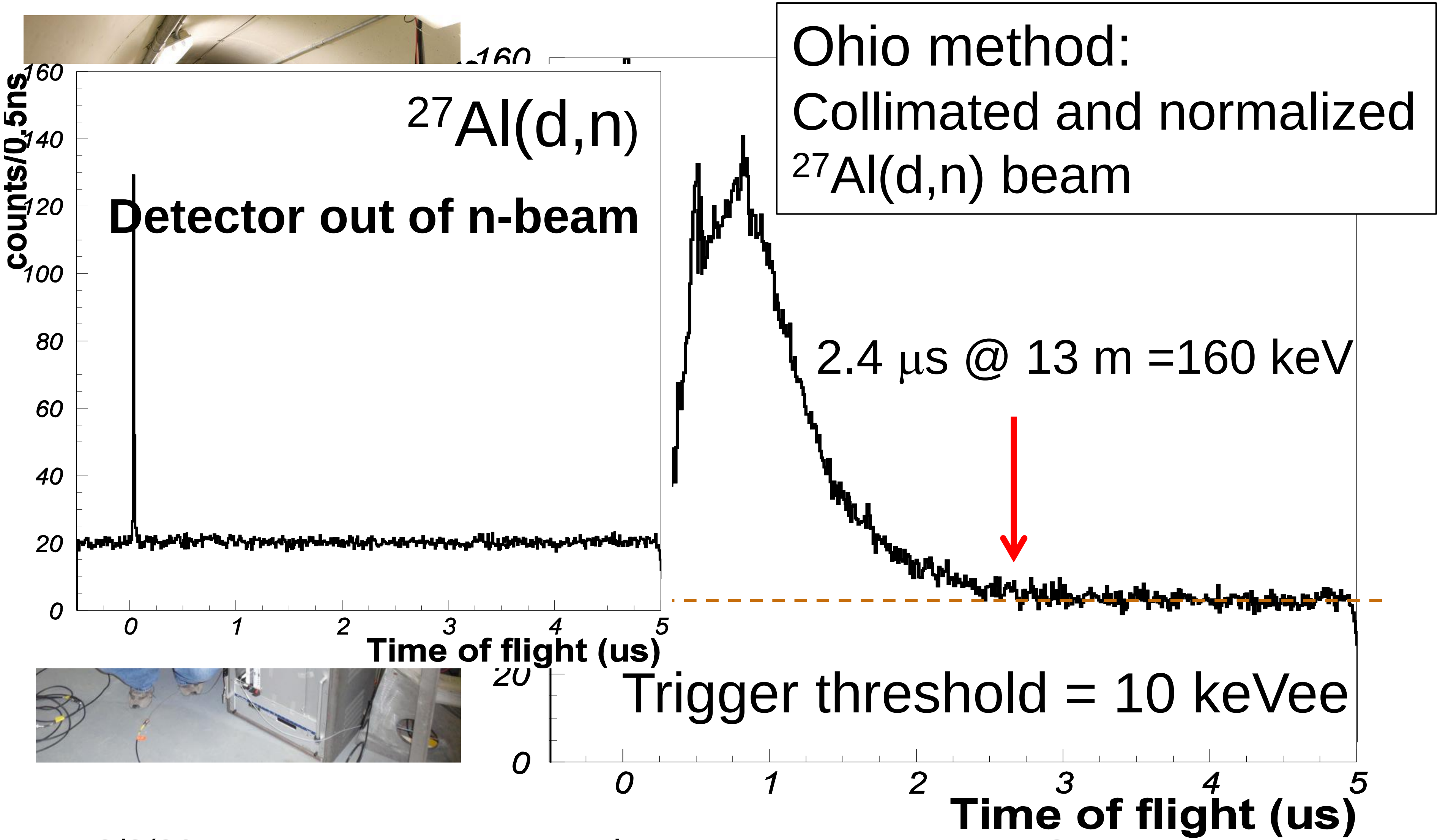


VANDLE efficiency measurement at Ohio U

Ohio method:
Collimated and normalized
^{27}Al(d,n) beam

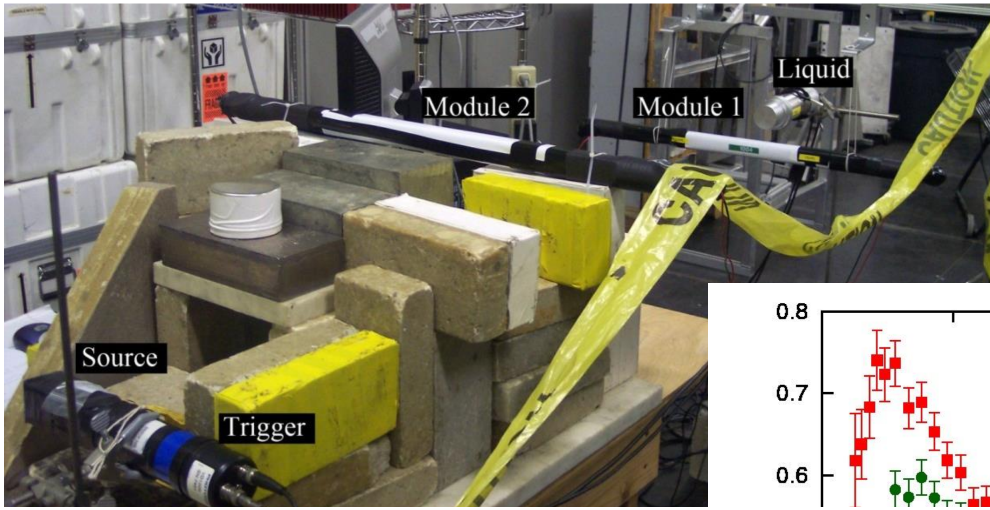


VANDLE efficiency measurement at Ohio University

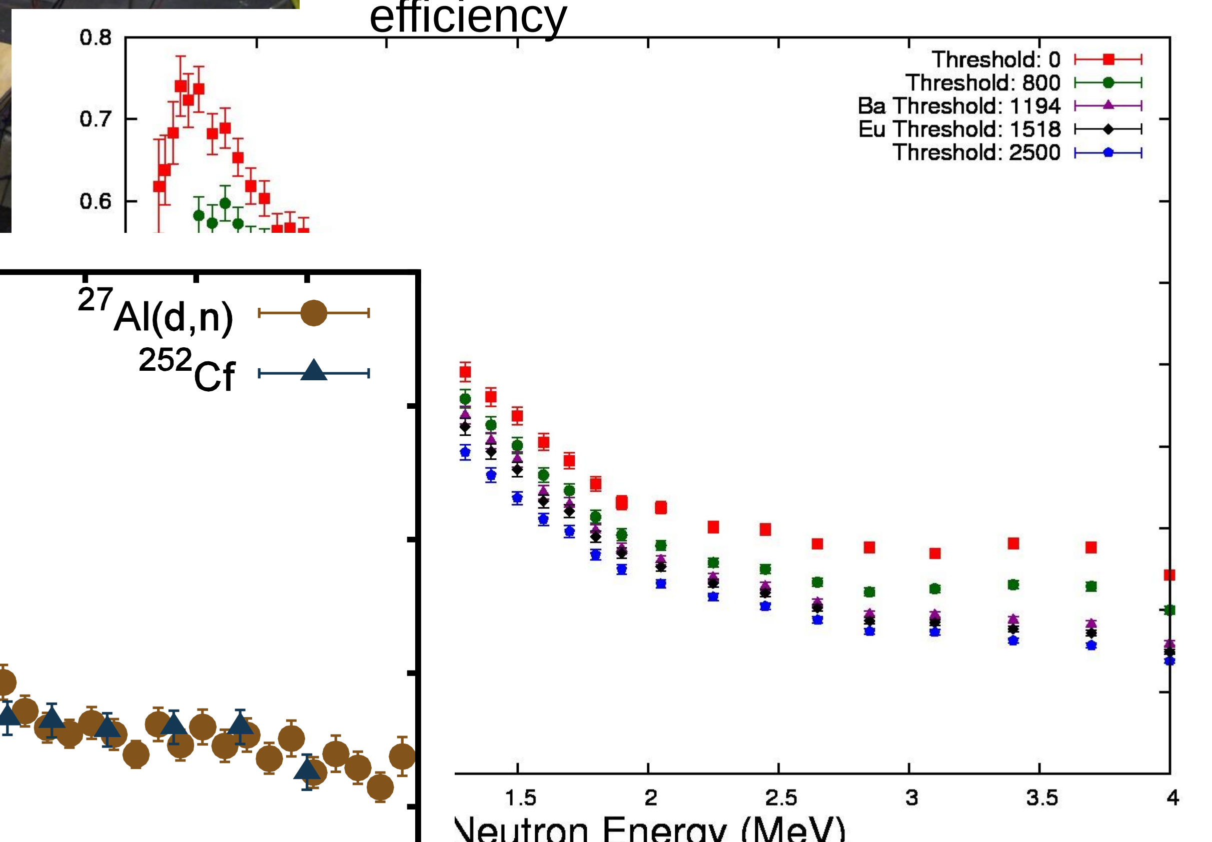


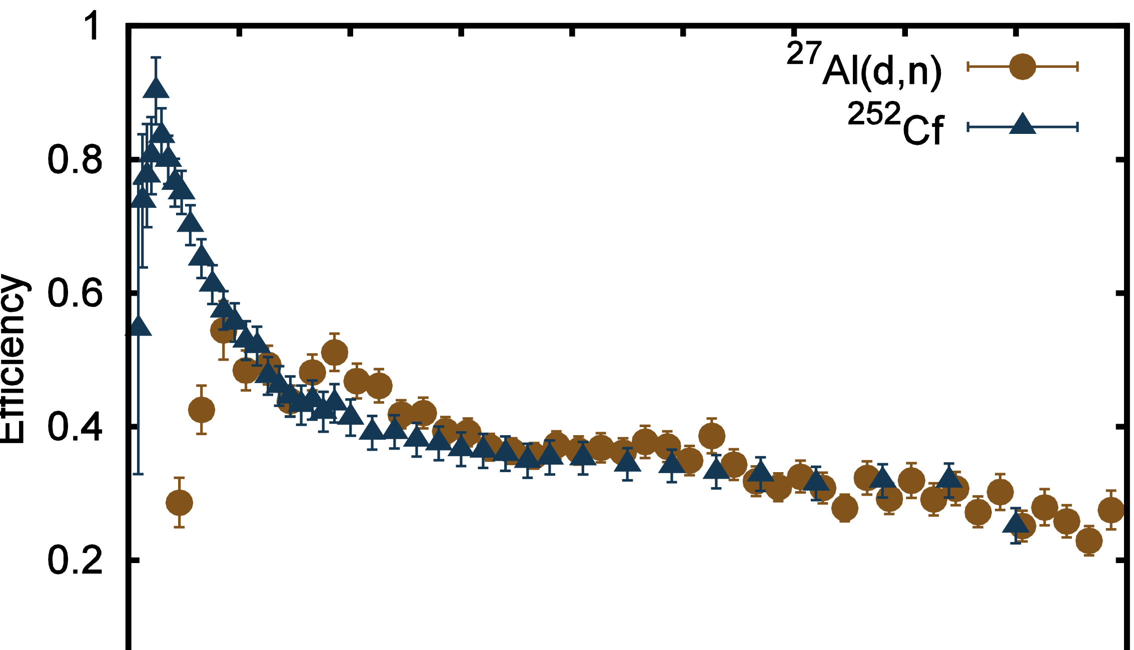
VANDLE efficiency @ ORNL

W.A. Peters & I. Spassova

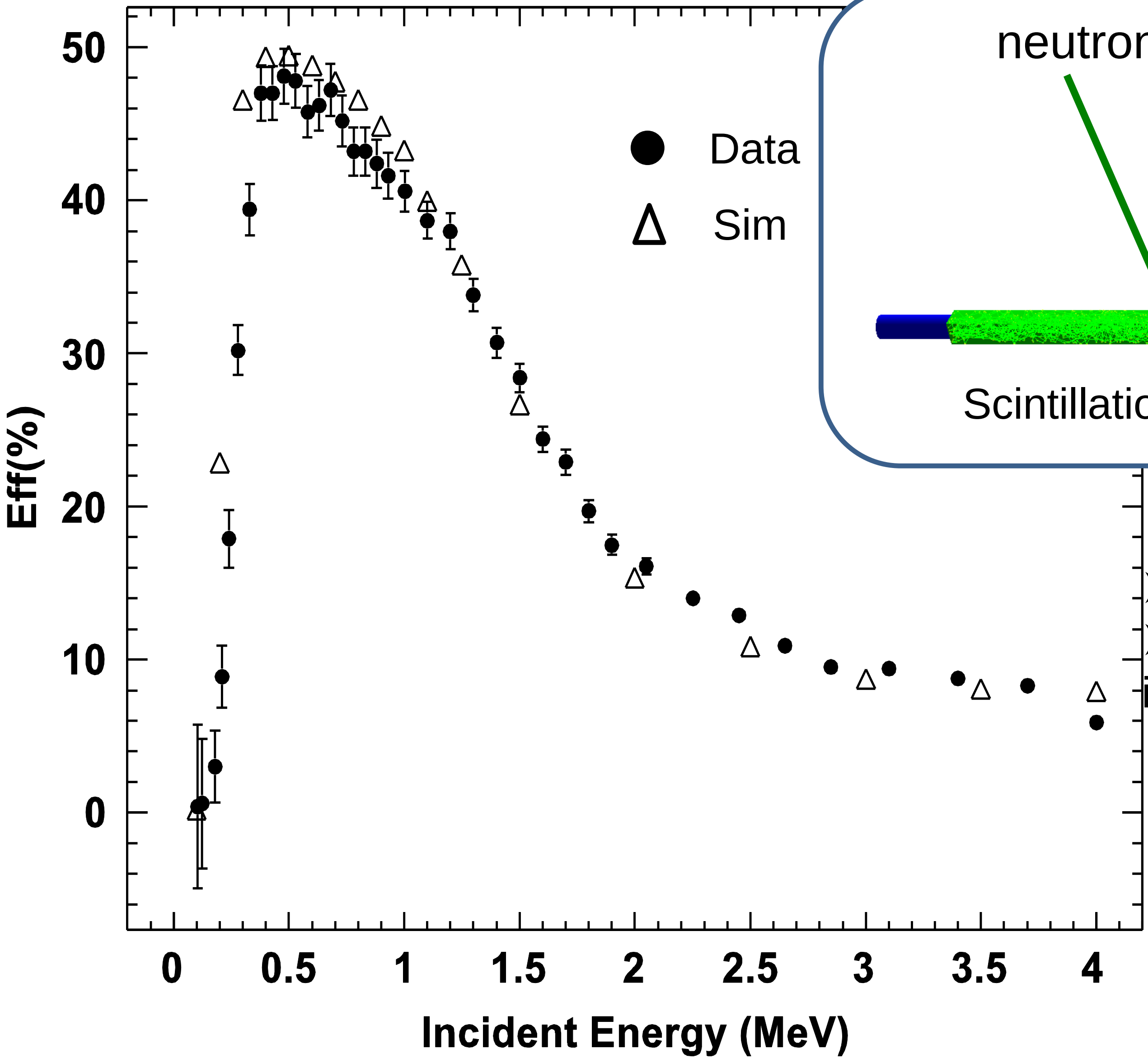


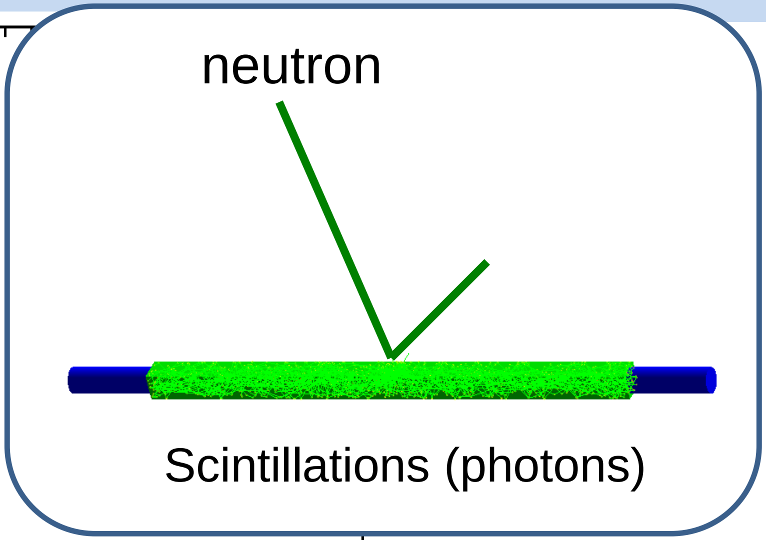
- Collimated ^{252}Cf source
- "shadowbar" measurement for scattered neutrons background
- Liquid scintillator normalized efficiency





Geant4 simulation of VANDLE bars

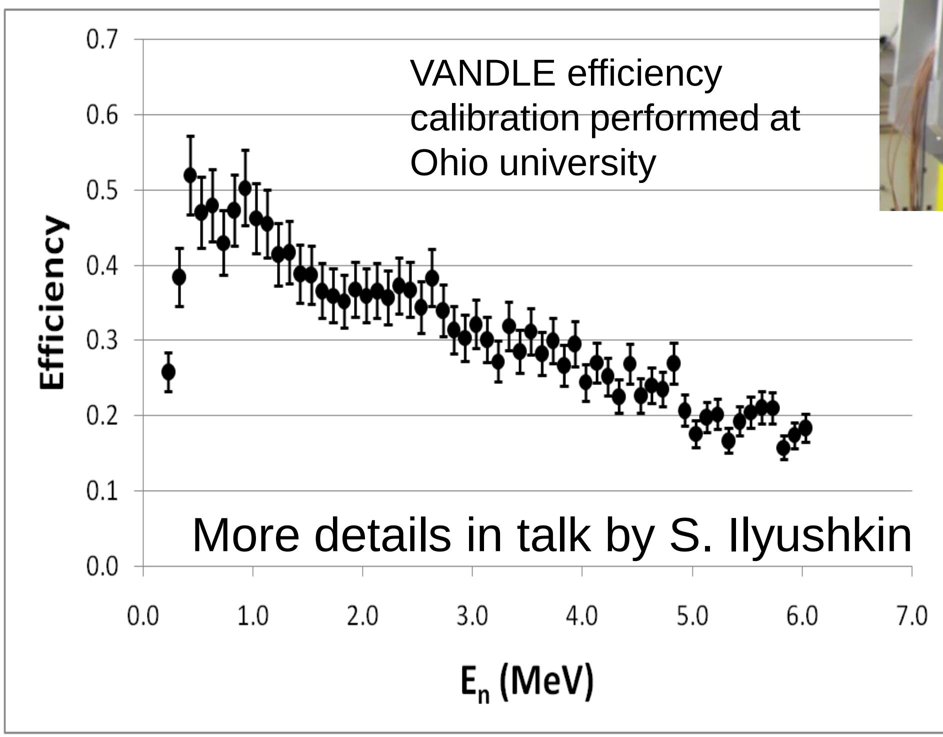


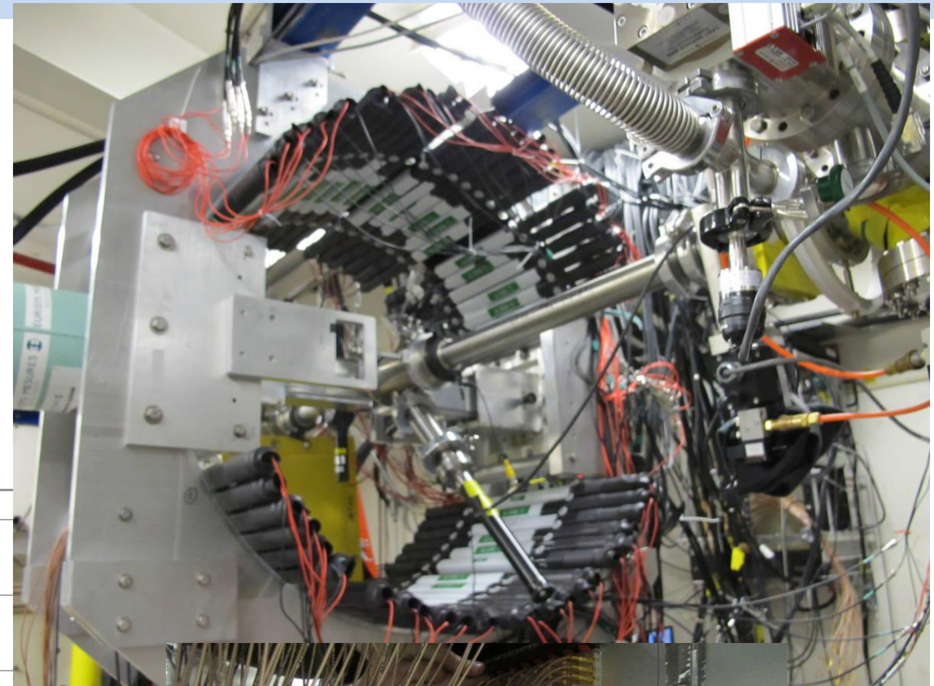


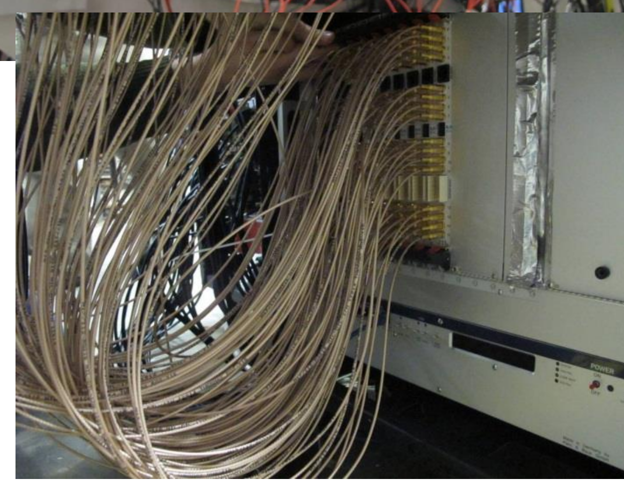
- 30 keVee threshold
- Geant4 Monte-Carlo includes:
  - Wrapping materials
  - Plastic scintillator
  - Photo-cathode acceptance

(III) Neutron Spectroscopy
The Versatile Array for Neutron Detection at Low Energies

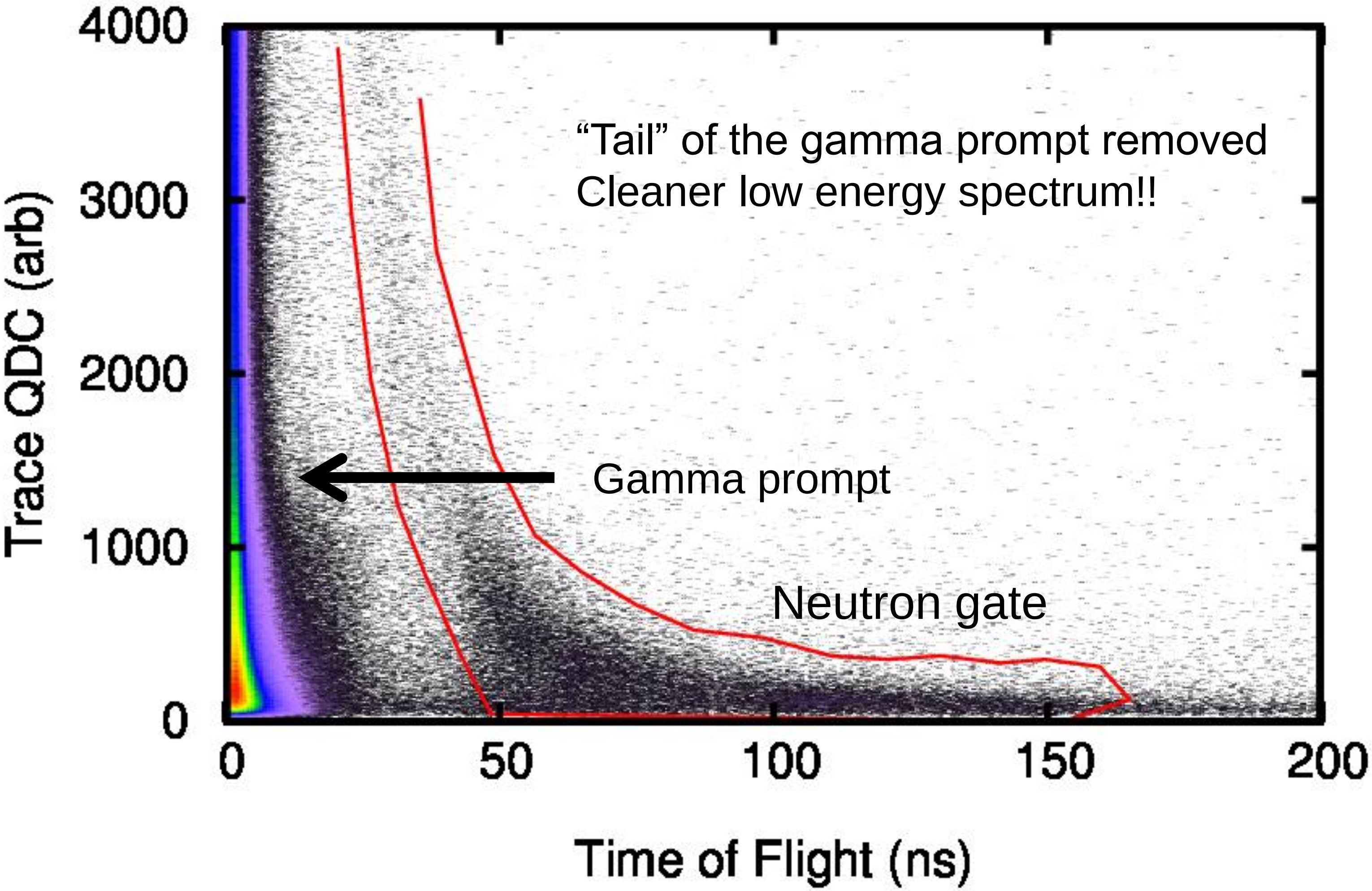
- 2 clovers, 3% efficient @ 1MeV
- 48 x 60 cm VANDLE bars
  - 45% efficiency/bar @ 1MeV
  - Ω = 10% (23%) of 4π
  - 40-60% β-trigger efficiency
  - 3% (6%) total efficiency @ 1MeV
- Fully instrumented using XIA's Pixie 16 digitizers





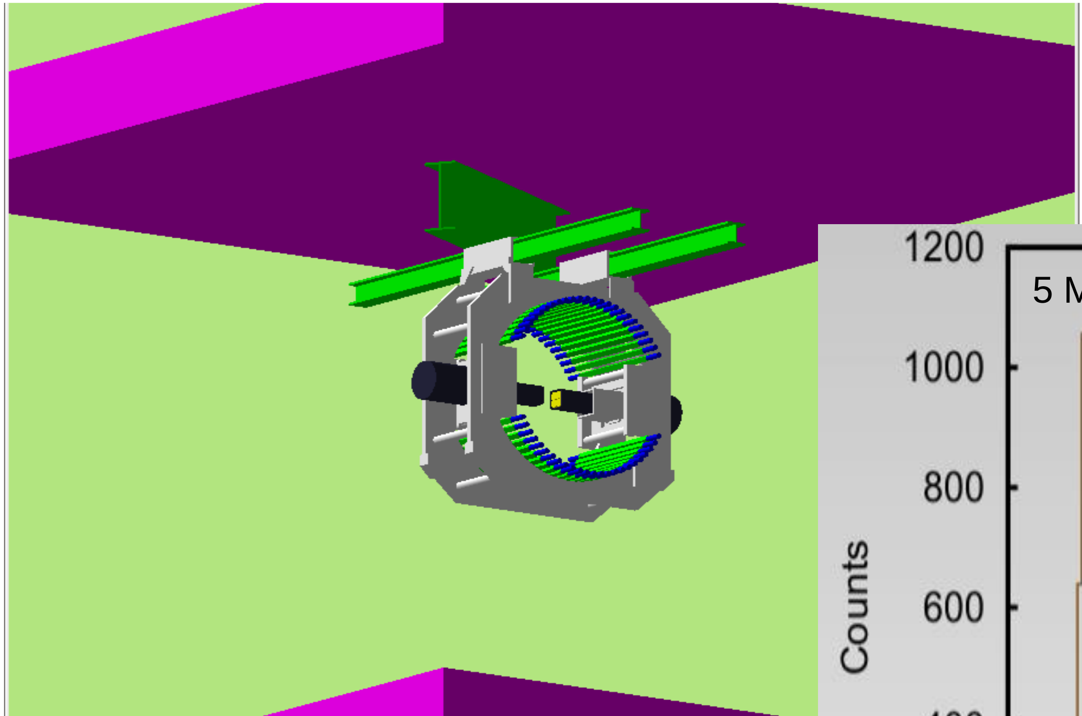


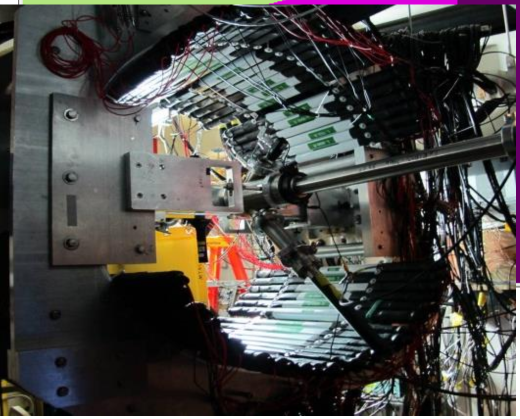
Light output vs Time of Flight: Neutron gate



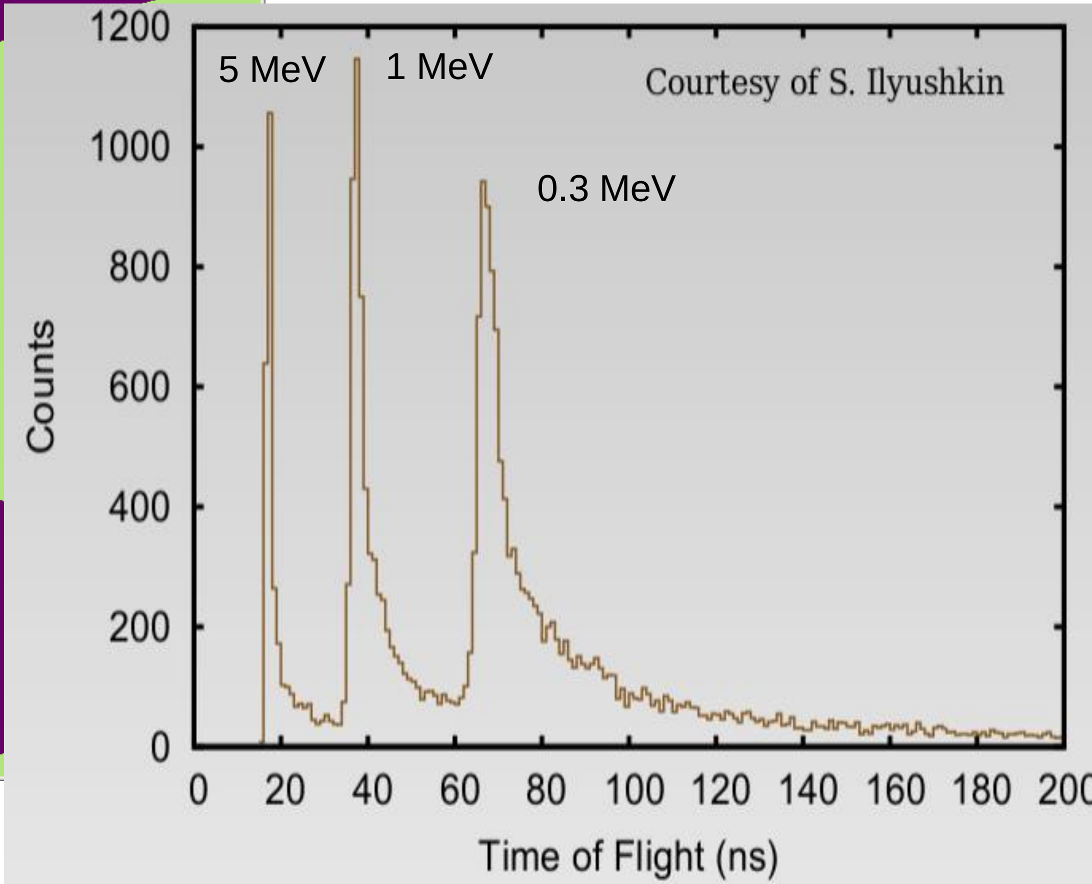
Monte Carlo simulation of LeRIBSS setup

S. Ilyushkin



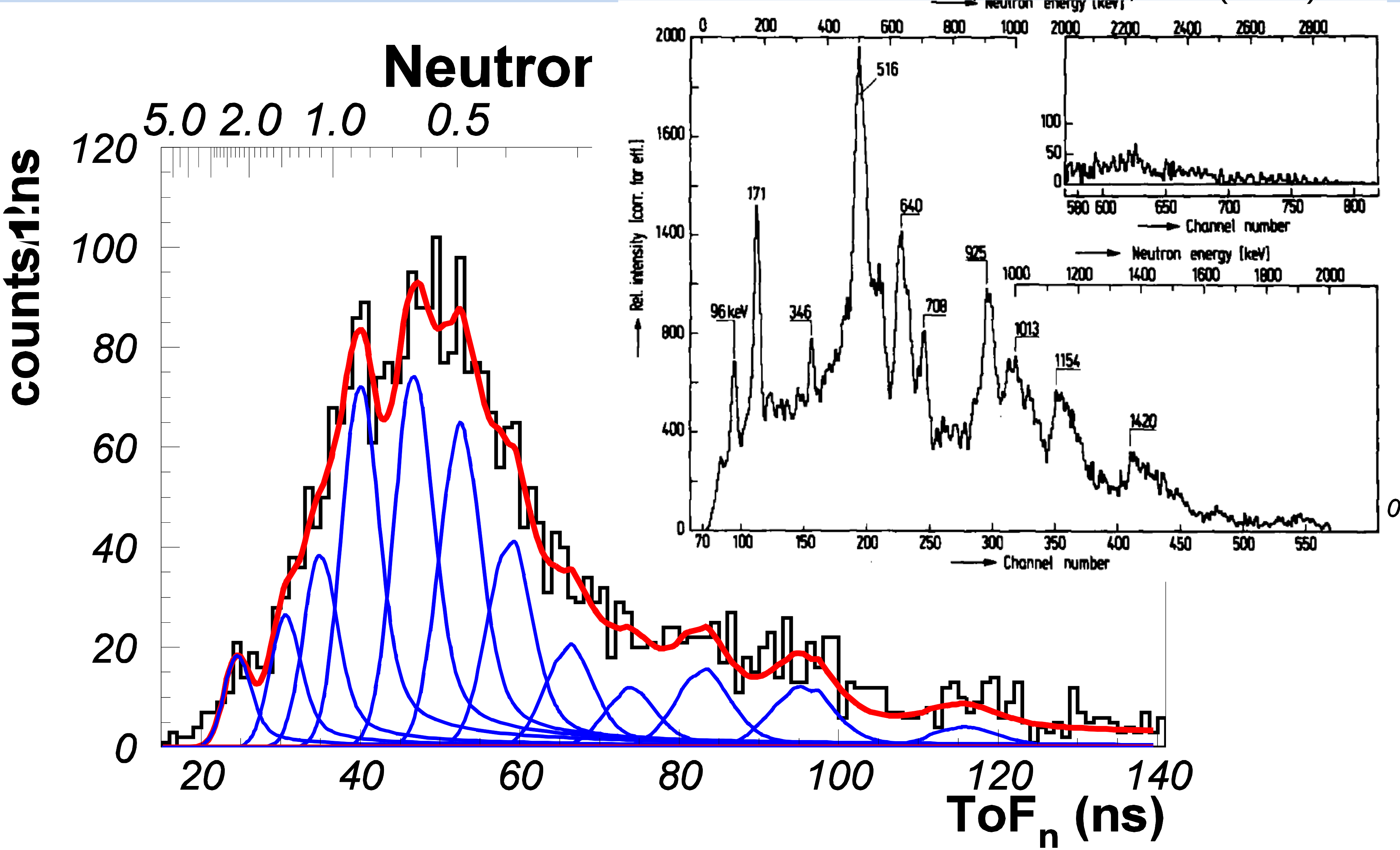


Isotropic, mono-energetic neutron source

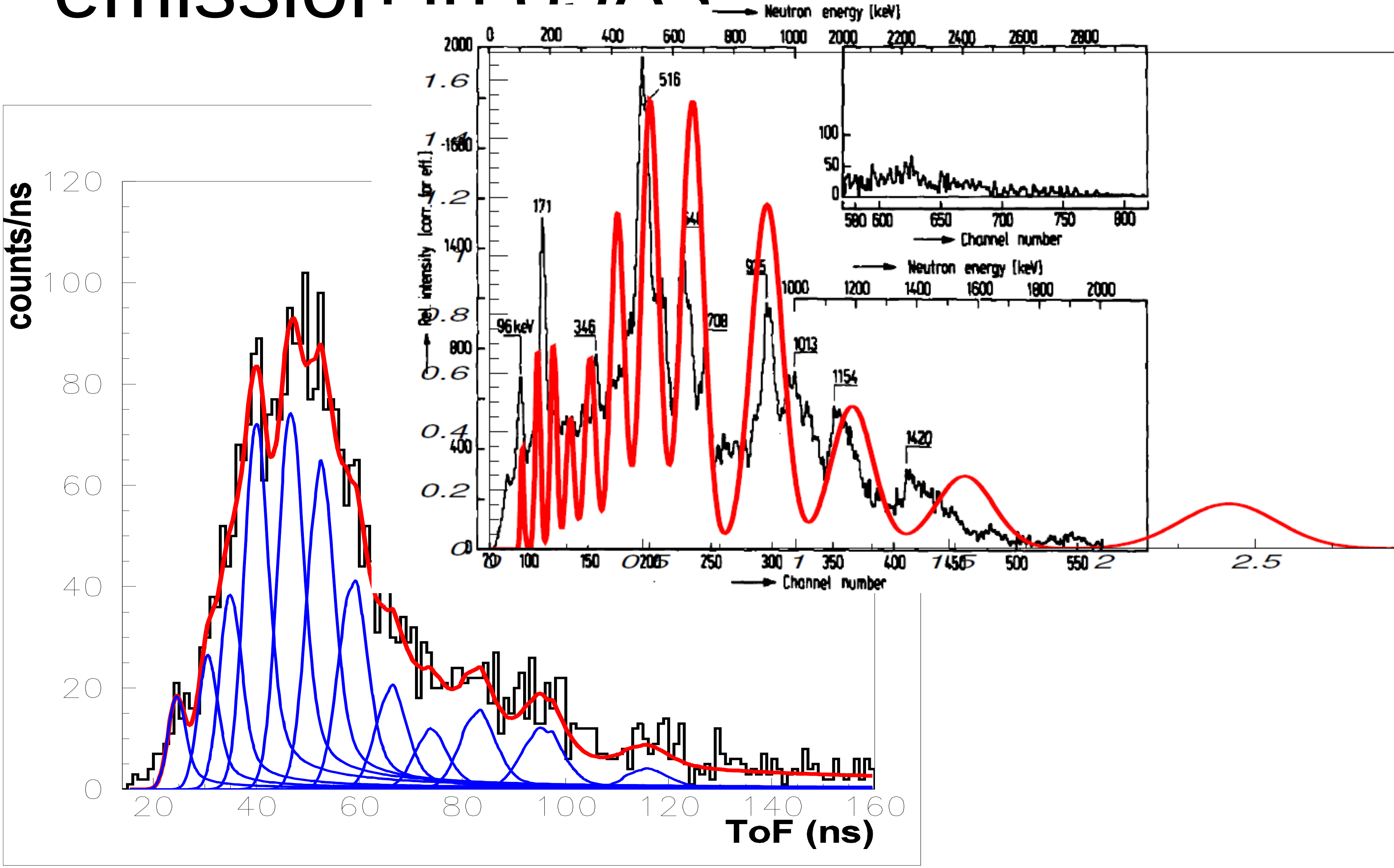


1-Neutron energy spectrum:
Beta-delayed neutron emission in ^{85}As

K.L. Kratz et al., NPA 317, 335 (1979)



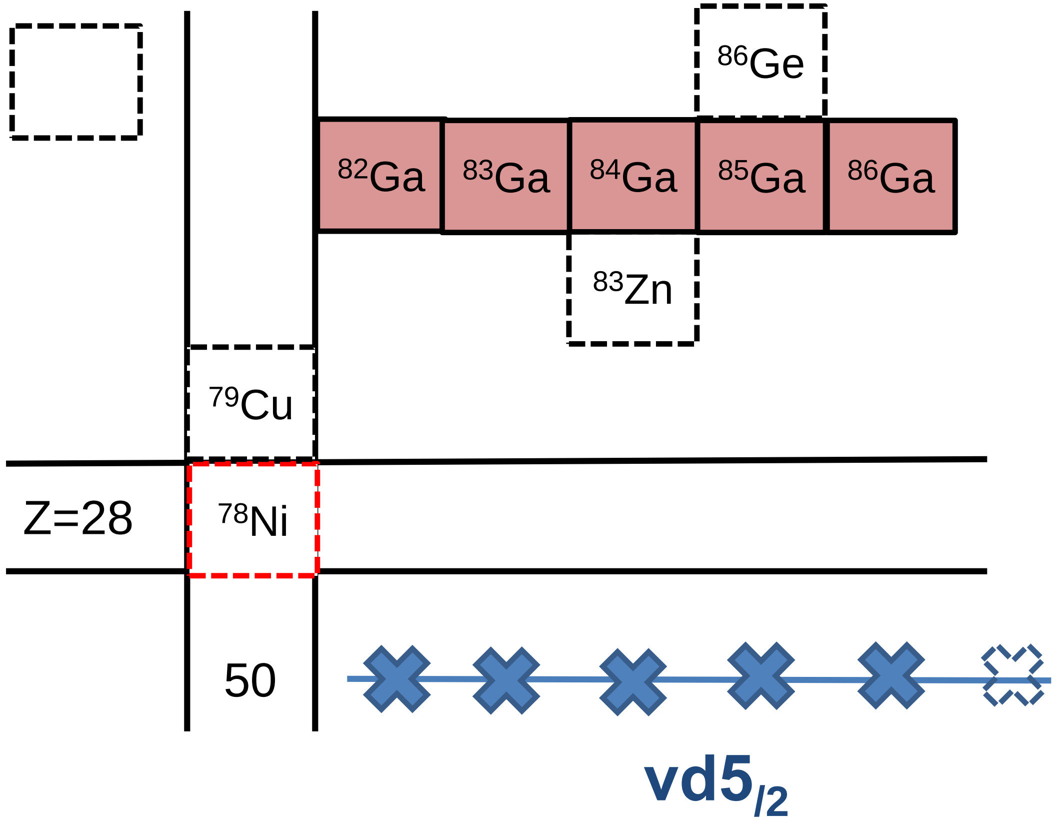
Low energy delayed neutron emission in 85As



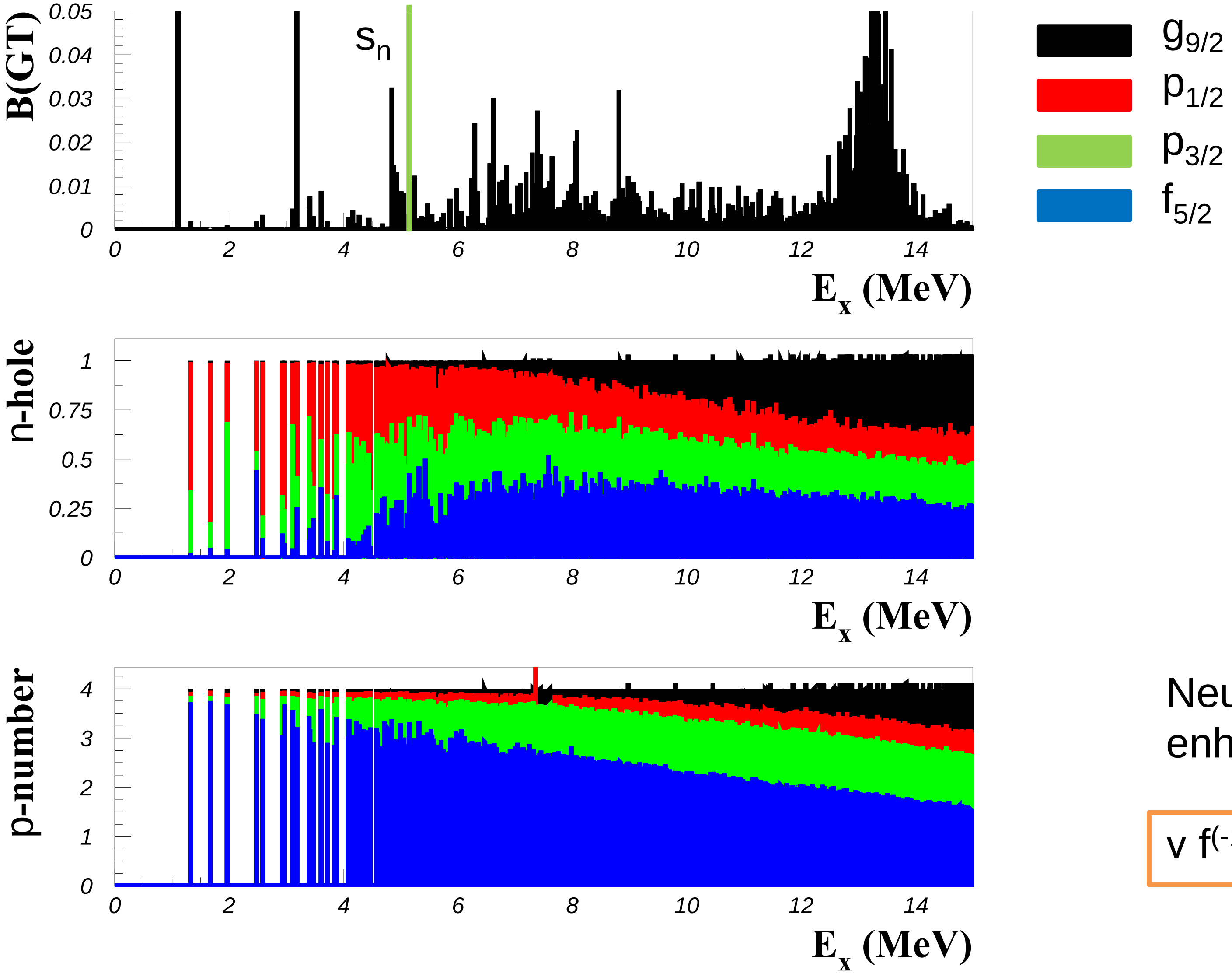
Why Cd?:
a sneak-peak beyond the N=50 shell closure

Furthest from stability at ISOLDE

- Ga isotopic chain offers a unique opportunity:
- Furthest from stability at Z~28
- Increasing $vd_{5/2}$ shell occupation for both mother and daughter



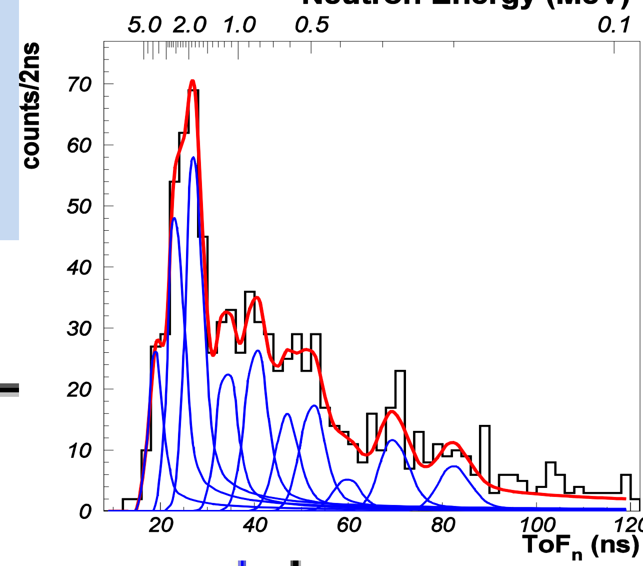
Shell Model Single Particle composition

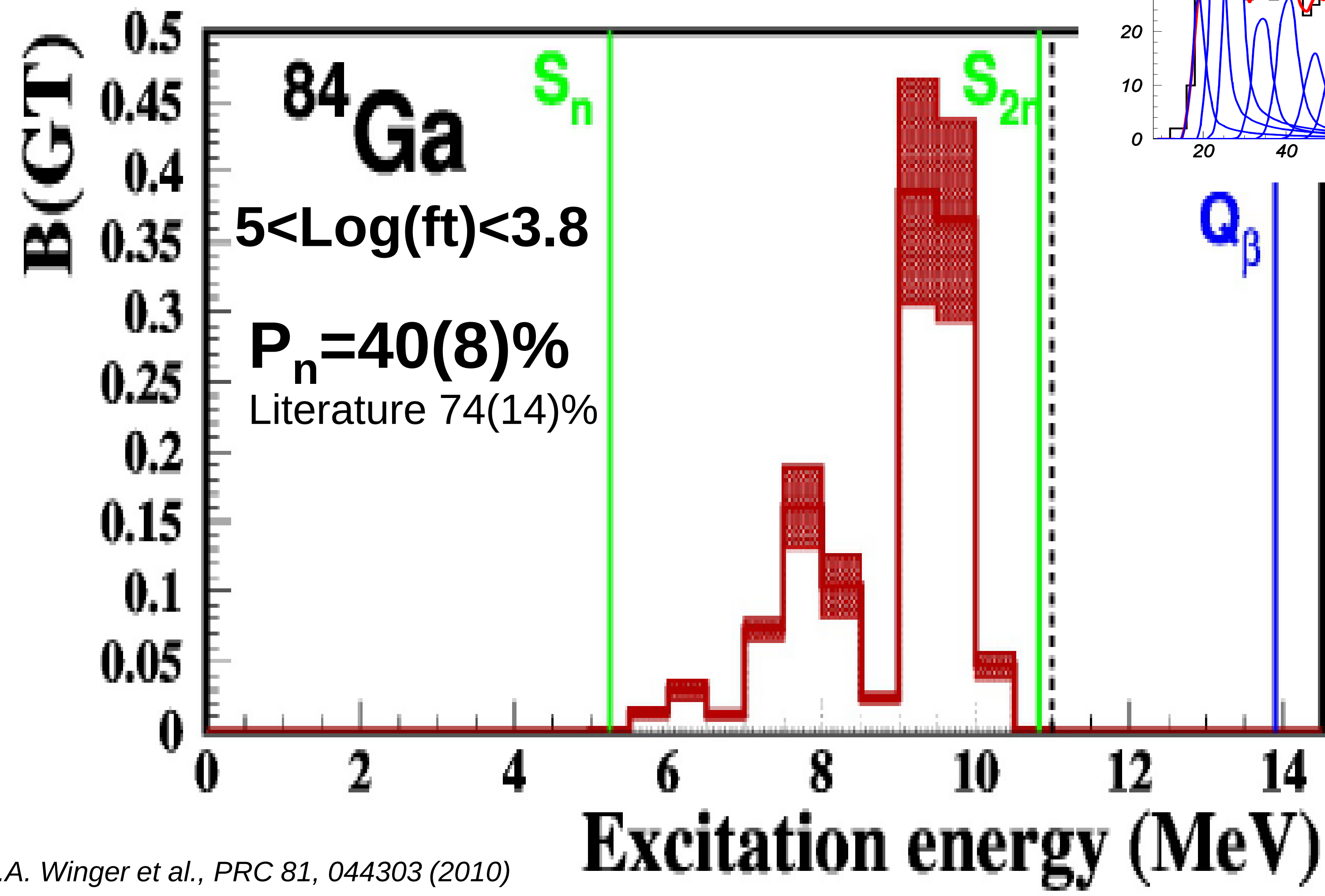


Neutron emission enhanced by

$\nu\, f^{(-1)}_{5/2} \rightarrow \pi\, f_{5/2}$

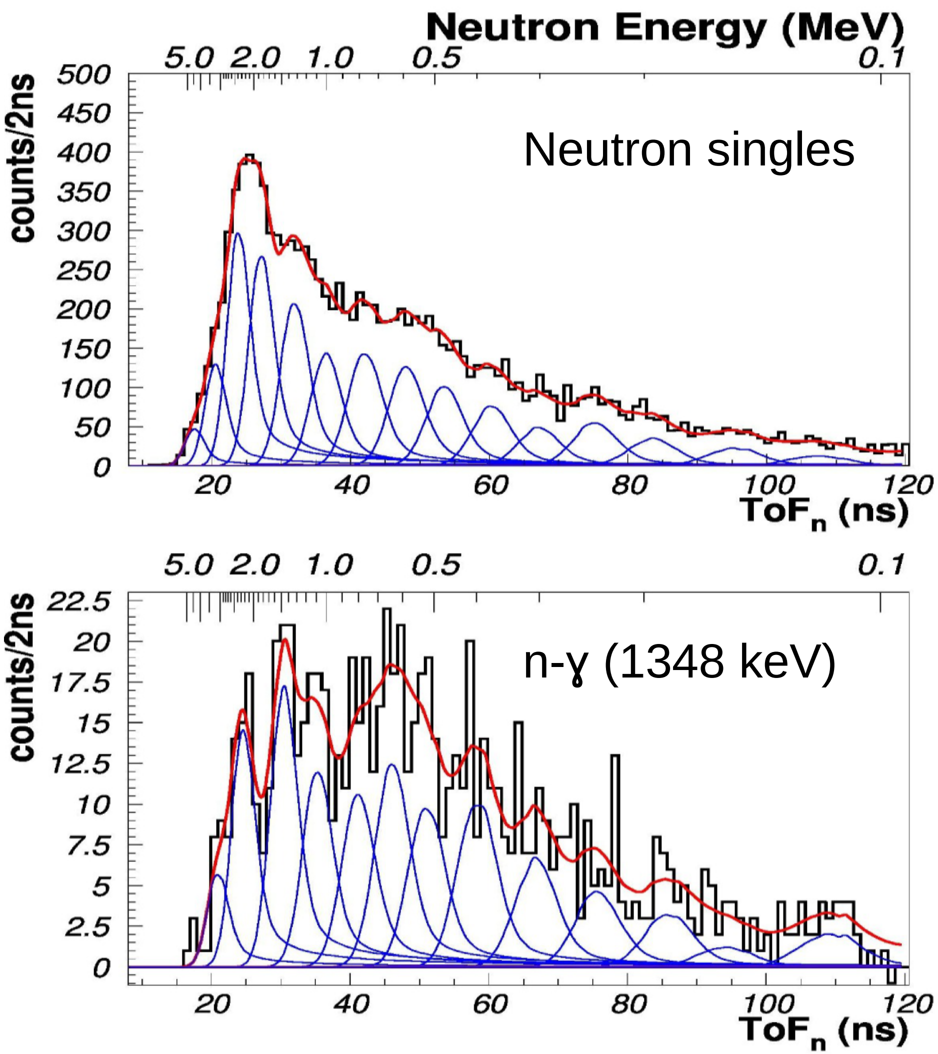
^{84}Ga B(GT) distribution

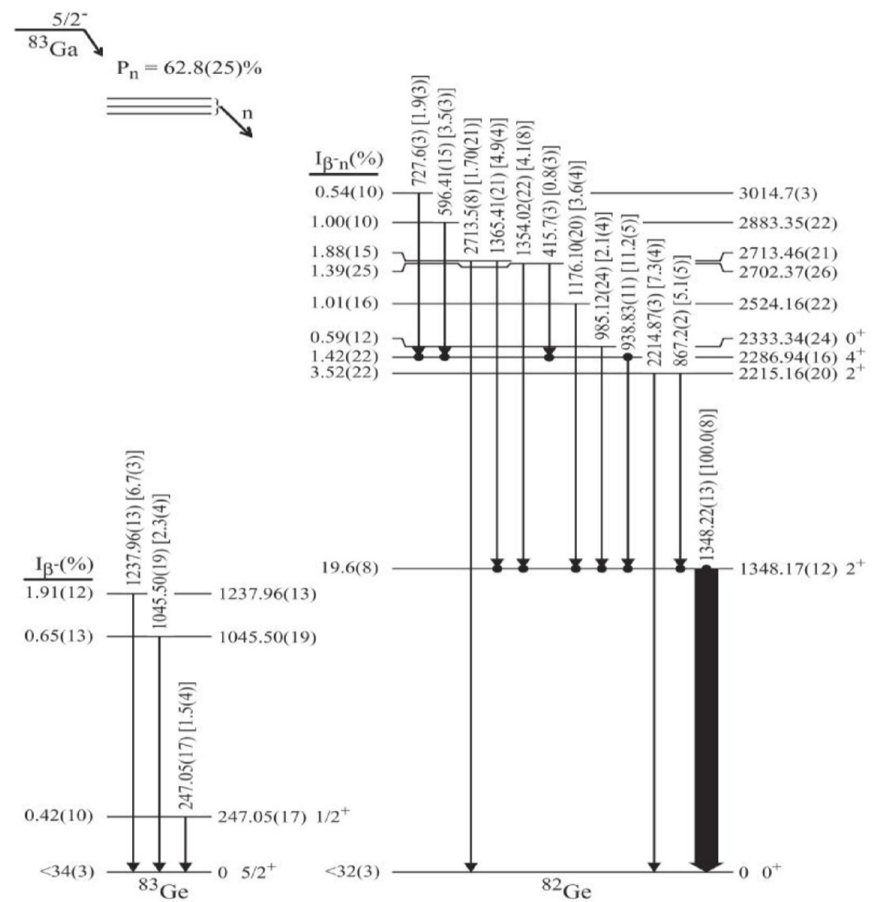


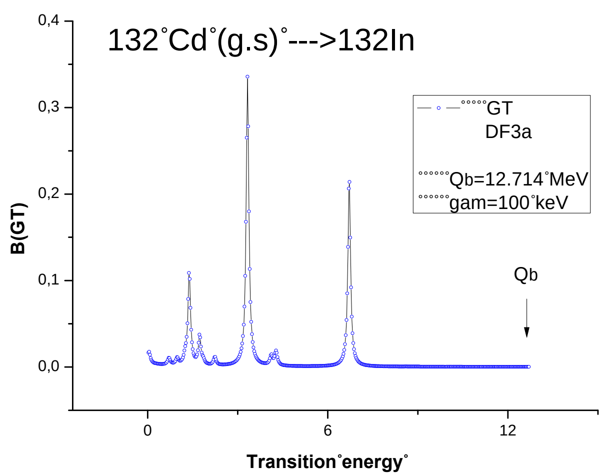


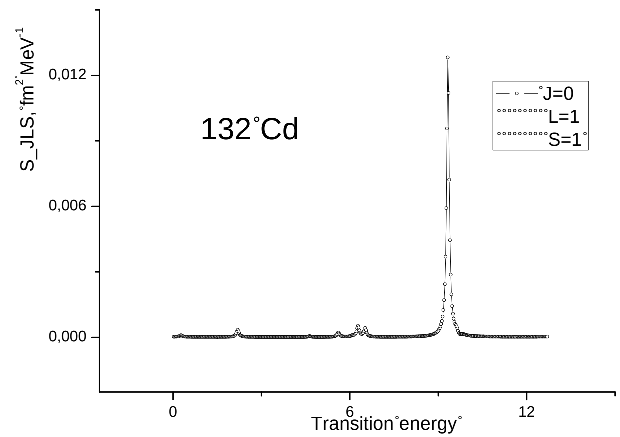
J.A. Winger et al., PRC 81, 044303 (2010)

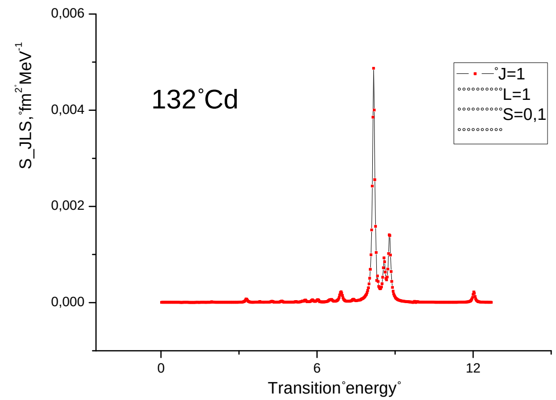
Neutron-gamma coincidences in ^{83}Ga beta decay



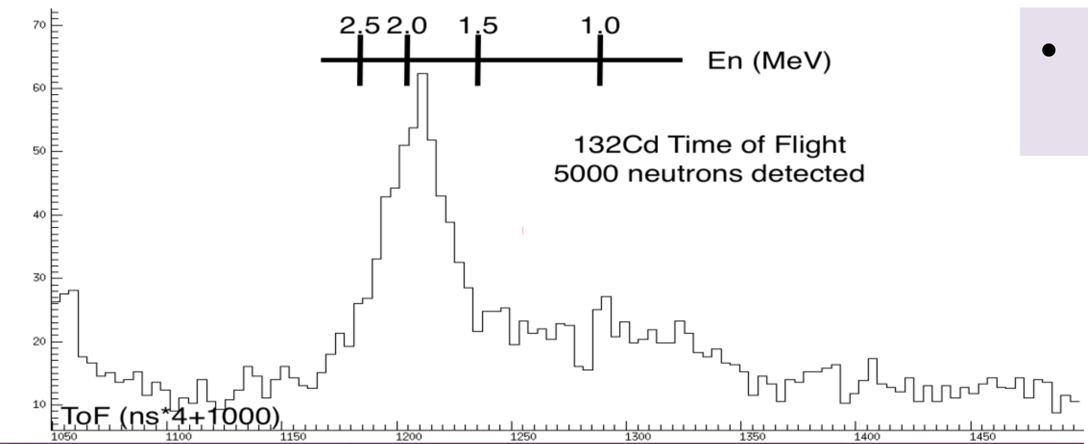



132˚Cd˚(g.s)˚--->132In
B(GT)
0,4
0,3
0,2
0,1
0,0
GT
DF3a
Qb=12.714˚MeV
gam=100˚keV
Qb
0
6
12
Transition˚energy˚


S_JLS,˚fm^2˚MeV^{-1}
0,012
0,006
0,000
132˚Cd
J=0
L=1
S=1˚
0
6
12
Transition˚energy˚


S_JLS,˚fm^2˚MeV^{-1}
0,006
0,004
0,002
0,000
132˚Cd
J=1
L=1
S=0,1
0
6
12
Transition˚energy˚

IS600: Beta-delayed neutron emission in ^{132}Cd



- Beta decay of ^{132}Cd:
  - 9 shifts with yield=0.5 μC^{-1}